# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**LINKING COMBAT SYSTEMS CAPABILITIES AND SHIP DESIGN THROUGH MODELING AND COMPUTER SIMULATION**

by

Christopher R. Pisani

September 2013

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**13. ABSTRACT (maximum 200 words)**

When designing combat vessels, the traditional approach has been to configure weapons and other operational systems around the hull. Such thinking may have been rooted in the idea that hull design is the highest priority, since it can translate into a speedier and more seaworthy vessel, thereby allowing the vessel to reach its destination and complete its mission on a timelier basis.

The traditional approach, however, has its shortcomings; once the ship is built, modifications to meet changing operational requirements can be costly and difficult to implement. Ship designers have long sought a methodology to identify such shortcomings by linking mission requirements with naval requirements in the early stages of ship design. The ongoing challenge has been to devise a synthesizing and modeling tool that enables designers to assess the trade-offs that may occur as design modifications are proposed.

The Naval Postgraduate School has taken on this challenge through its design concept using Model-Based Systems Engineering (MBSE). This thesis considers how MBSE might extend its use of simulation and modeling to better link architectural ship designs to combat system requirements. This thesis considers such linking and identifies a synthesizing tool that may facilitate the synthesizing and modeling process.

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# LINKING COMBAT SYSTEMS CAPABILITIES AND SHIP DESIGN THROUGH MODELING AND COMPUTER SIMULATION

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# ABSTRACT

When designing combat vessels, the traditional approach has been to configure weapons and other operational systems around the hull. Such thinking may have been rooted in the idea that hull design is the highest priority because it can translate into a speedier and more seaworthy vessel, thereby allowing the vessel to reach its destination and complete its mission on a timelier basis.

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The Naval Postgraduate School has taken on this challenge through its design concept using Model-Based Systems Engineering (MBSE). This thesis considers how MBSE might extend its use of simulation and modeling to better link architectural ship designs to combat system requirements. This thesis considers such linking and identifies a synthesizing tool that may facilitate the synthesizing and modeling process.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ASNET | Application System for Naval Evaluation and Testing |
| ASSET | Advanced Ship and Submarine Evaluation Tool |
| ASuW | Anti-Surface Warfare |
| CETENA | Centro Per GLI Studi Di Tecnica Navale |
| CORE | Systems Engineering Software from Vitech Corporation |
| D | Drag: the resistance of the ship |
| DOE | design of experiments |
| EHP | Effective Horsepower |
| Excel | Microsoft Corporation’s Excel software program |
| $Fn_{vol}$ | Volumetric Froude number; $Fn_{vol} = V/\sqrt{[g(\Delta vol)^{1/3}]}$ |
| g | Gravitational constant (9.8 $m/s^2$) |
| HP | horse power |
| HSSL | High Speed Sea Lift |
| IHDE | Integrated Hydrodynamic Design Environment |
| INCOSE | International Council on Systems Engineering |
| JANE’S | Jane’s Fighting Ships |
| JMP | John’s Macintosh Project (a statistical analysis software program) |
| LEAPS | Leading Edge Architecting for Prototyping Systems |
| L | Lift: the weight of the ship |
| L/D Ratio | Lift to Drag Ratio |
| LT | Long Tons (2240 pounds) |
| MANA | Map Aware Non-Uniform Automata |
| MBSE | Model-Based Systems Engineering |
| MIO | Maritime Interdiction Operations |
| MOE | Measure of Effectiveness |
| MOP | Measure of Performance |
| MV | motor vessel |
| NATO | North Atlantic Trade Organization |
| NAVSEA | Naval Sea Systems Command |

| | |
|---|---|
| NCCA | Naval Center for Cost Analysis |
| NICOP | Naval International Cooperative Opportunities in Science & Technology Program |
| NPS | Naval Postgraduate School |
| NSWCCD | Naval Surface Warfare Center Carderock Division |
| OEM | Operational Evaluation Model |
| OMOE | Overall Measure of Effectiveness |
| ONR | Office of Naval Research |
| OPC | Overall Propulsive Coefficient; OPC = EHP/SHP |
| OPV | Offshore Patrol Vessel |
| OR | Operations Research Department |
| OSN | Orrizonte Sistemi Navali |
| PBDC | Performance-Based Design Continuum |
| PCC | Pearson Correlation Coefficient |
| PRONTO | Partnership for Research on Naval Technology and Operations |
| RSDE | Rapid Ship Design Environment |
| R Square | Pearson’s Correlation Coefficient (PCC) Squared |
| SAR | Search and Rescue |
| SE | Department of Systems Engineering (NPS) |
| SFC | Specific Fuel Consumption |
| SHP | Shaft Horsepower |
| SSM | Ship Synthesis Model |
| UAV | Unmanned Aerial Vehicle |
| USS | United States Ship |
| V | Ship speed in meters per second |
| Vk | Ship speed in knots |
| $\Delta$vol | Displaced volume in cubic meters |

# EXECUTIVE SUMMARY

The question presented by this thesis is whether a methodology can be devised that can enable and encourage ship designers to synthesize proposed models in the early stages of ship design in order to better coordinate operational needs with naval architectural requirements.

The conclusion is that, yes, the Model-Based Systems Engineering (MBSE) design concept can be used to allow a ship synthesis model to link ship design factors with ship operational considerations that were generated from operational modeling. Further, the five-parameter method can serve as a useful tool in that effort. However, it is recommended that it be fortified by additional research to increase its credibility level, which can be accomplished by validating its use through traditional synthesis and modeling tools.

The analysis portion of this thesis briefly reviews some traditional tools and identifies a more recently developed tool to quickly test the effects of design modifications in the early stages of ship design. While it is true that the basic principles of naval and engineering science have not changed, capturing the effects of any proposed change through the use of synthesis and simulation tools such as Advanced Ship and Submarine Evaluation Tool (ASSET) and its recent modifications continue to be a formidable challenge.

More specifically, the thesis analysis considers, endorses, and expands upon a methodology and tool created in recent years as a simple and rudimentary method for developing a design space for high-speed cargo ships. The theorist who devised the tool points to five basic metrics that, when combined into an Excel-based dashboard, suggest that the tool may be useful to quickly predict the effects on the physical space as changes in operational space are proposed. Typically, such changes can be useful when predicting a ship's speed, range, and payload carrying ability. The testing of this tool was a multistep process, including the conversion of certain metrics typical for a cargo ship to those typical of a combat vessel.

The five parameters used by the tool include (1) lift to drag ratio (L/D Ratio), (2) overall propulsion coefficient (OPC), (3) specific fuel consumption (SFC), (4) weight of the power plant, and (5) weight capacity of cargo carrying capacity. The L/D Ratio reflects the amount of resistance that a ship may encounter as it moves through water. The OPC is the ratio of the effective horsepower to the shaft horsepower installed on the ship. The SFC measures the efficiency of the ship in burning its fuel. The weight of the power reflects the combined weight of fuel and the power plant equipment in terms of horsepower that it must carry. Lastly, the cargo carrying capacity states the maximum weight of payload that can be carried.

The testing performed by this author included applying the five parameters to a cargo ship and three combat vessels. The purpose of the test was to monitor what effects would occur as a ship's characteristics or capabilities in speed, range, and payload carrying ability are altered. A dashboard was devised to illustrate the test results, as well as to suggest the approximate length and beam that would be required of a ship in order to accommodate the proposed speed, range, and payload requirements.

The results of the test are illustrated in 4 ships designs. Ship Design #1 is the cargo ship design used by the originator of the five-parameter method. It is the first design model presented, since Ship Design(s) #2 through #4 are based upon that design. As such, Ship Design #1 serves as the initial baseline against which the other designs are compared. Ship Design #2 illustrates a hypothetical military vessel with the same characteristics as Ship Design #1, except that the L/D ratio is adjusted to reflect an L/D ratio and Froude number for a typical military vessel. Ship Design #3 follows the formula used for Ship Design #2, but uses data from an Offshore Patrol Vessel, a Brazilian Amazonian Class OPV, so as to quickly determine if it could meet the ship operator's threshold requirements. Once it was determined that it cannot meet those requirements, then an arbitrary adjustment was made to reduce the displacement from 12,000 LT to 8,000 LT, so as to find an acceptable design. This is illustrated in Ship Design #4.

In developing the five parameters, it was necessary to use statistical analysis, including regression analysis, to evaluate how close a relationship might exist between certain sets of data. By doing so, the reliability of a formula as a predictor of consequences as ship characteristics are modified could be better evaluated. This topic is covered in detail in the discussion of parameter #1 (i.e., L/D Ratio).

In summary, the MBSE design concept can be used to allow a ship synthesis model to link ship design factors with ship operational considerations that were generated from operational modeling. The five-parameter method can serve as a useful tool in that effort. However, it needs to be fortified by additional research to increase its credibility level, which can be accomplished by validating its use through traditional synthesis and modeling tools.

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# I. INTRODUCTION

## A. BACKGROUND

Traditional naval architect design methods have called for operational systems, such as helicopter flight decks, weaponry, and radar, to be configured based upon the hull design, rather than vice versa (MacCalman 2013). The limitations of such a design methodology become apparent later in the ship's life cycle when modifications to operational systems can be too costly or impossible to implement either because the hull design precludes such modification or the tradeoffs make such modifications cost prohibitive. In short, if the mission-related systems are limited to what will "fit" within the hull or what will work along with the ship's naval-related architecture, then the mission capabilities may be limited as well, possibly jeopardizing the success of the ship's mission. This weakness in the current design methodology may be minimized if the ship designers can expose such limitations before the ship is built.

The Office of Naval Research (ONR) has engaged the Department of Systems Engineering at the Naval Postgraduate School (NPS) to devise and demonstrate a methodology which will enable ship designers to readily determine whether a proposed design may be feasible when considering certain types of missions using off-shore patrol vessel(s) (OPV) (Lineberry 2012). The department team leaders and NPS students involved in the project believe that the Model Based Systems Engineering (MSBE) design concept can be a framework within which this task may be accomplished (MacCalman 2013).

**Model-Based Systems Engineering (**MBSE) has been described by the International Council on Systems Engineering (INCOSE) as follows:

> The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. In particular, MBSE is expected to replace the document-centric approach that has been practiced by systems

> engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of systems engineering processes (INCOSE 2007, 15).

In turn, INCOSE describes a “system” as follows:

> A system can be broadly defined as an integrated set of elements that accomplish a defined objective. People from different engineering disciplines have different perspectives of what a “system” is. For example, software engineers often refer to an integrated set of computer programs as a “system.” Electrical engineers might refer to complex integrated circuits or an integrated set of electrical units as a “system.” As can be seen, “system” depends on one’s perspective, and the “integrated set of elements that accomplish a defined objective” is an appropriate definition (INCOSE 2004, 10).

In its simplest terms, MBSE has been described by others as a multi-phased modeling process used to determine how well the components of multiple systems work with one another from an engineering standpoint through modeling instead of paper-based methods (Buede 2011, 2; INCOSE 2007, 15). Systems for a ship would include not only the hull and propulsion system, but also an immense amount of hardware, software, and personnel needed to operate the ship, and so they must all be considered in the MBSE modeling process (Choi 2009). Additionally, a major advantage of the MBSE modeling is that the systems can be tested before any final design is approved, thereby reducing the risk of possibly time-consuming and costly redesigns. MBSE and its application to the ship design process, as proposed by the NPS team, are discussed in detail in the Methodology chapter of this thesis.

The ONR project has been an on-going project at NPS for several years. During that time, various NPS students and other team members have addressed various segments of the MBSE design paradigm to determine how MBSE might apply when designing OPVs. As relating to this thesis, the prior studies have addressed what the operational needs might be for several types of missions, including search and rescue (SAR), maritime intercept operations (MIO), and anti-surface warfare (ASuW). Again, the mission of this thesis is to devise a methodology to link those operational needs with naval architectural requirements when designing the physical ship. Those prior studies are discussed briefly in the Methodology chapter and should provide the reader with a more comprehensive view of how the NPS use of the MBSE design might be considered when designing OPVs for such missions.

## B. SHIP OF CHOICE—OFFSHORE PATROL VESSEL (OPV)

The OPV is an appropriate choice for developing and testing the MBSE approach. One reason is that OPVs have become even more popular in recent years. *The Offshore Patrol Vessels: Sector Report 2013*, reports that [a]t least 19 countries are known to have a total of 112 OPVs on order and plans for another 190 at a value of over $45 billion. The total number of OPVs on order has increased by 11% in the last 2 years, while the number planned has also increased by 27%.

The popularity of OPVs may be easy to explain. They are more maneuverable in littoral waters and less costly to purchase and maintain than a destroyer or frigate (McKeown 2012). While OPVs cannot carry as many weapons systems as might a destroyer or a frigate, they do have the ability to traverse oceans as do destroyers and frigates (McKeown 2012). Moreover, data from *Jane's Fighting* Ships (2012) indicate that, generally speaking, are capable of carrying a helicopter, guns of various calibers, cannons, missiles, and a crew of up to 100, while achieving speed of at least 25 knots and a range of several thousand nautical miles, all within with a displacement of up to 2,300 long tons, a length of 300 feet, and a beam of 45 feet. Further, an OPV can support a number of weapons and other mission-specific systems that are modular, so they may be easily removed or replaced, as needed (Lineberry 2012). Figure 1 depicts a notional design for an OPV.

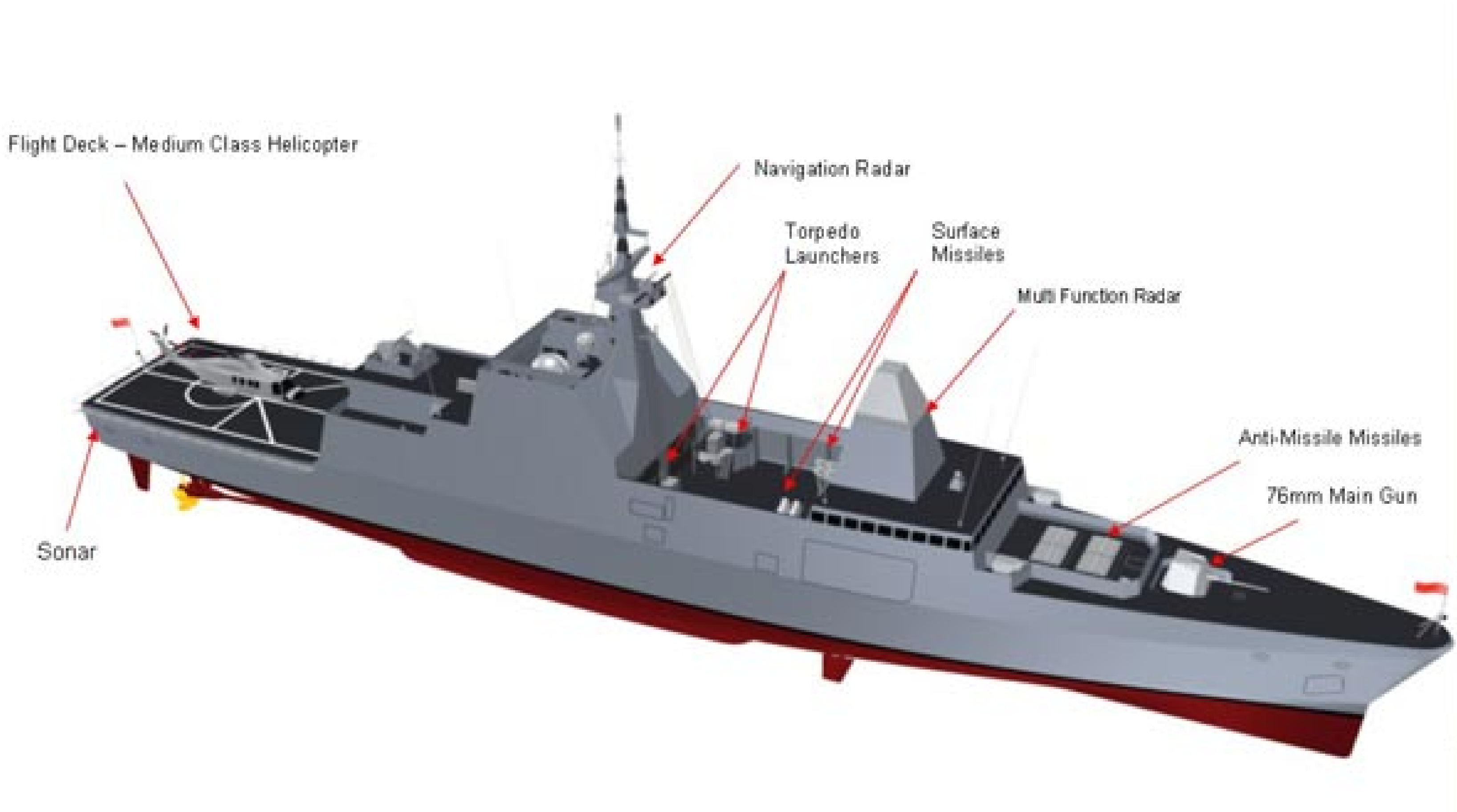


Figure 1. Notional OPV Design (Harpoon Database 2011; Welch 2011)

## C. OPV MISSIONS

Based on an oceanic-political view, the major probability of conflict could lie in four categories: economic-maritime disputes, piracy/drug trafficking, illegal use of natural resources, catastrophes and humanitarian emergencies within the littoral water boundary. Functions can be mapped into operating maritime safety and security sub functions and executed into mission capabilities for a relatively simple, light, and cost-effective ship to act in these conflicts. SAR, MIO, and ASuW were the missions analyzed to aid the ONR project and prove the MBSE concept.

Three recent theses by NPS students from the Operations Research Department examined the operational effectiveness of the OPV in performing SAR, MIO, and ASuW missions. Additional studies have been conducted by other former NPS students concerning related issues, such as cost and human systems integration (HSI) concerns for OPVs, but those studies are beyond the scope of this thesis. A brief summary of the relevant theses follow.

### 1. Maritime Search and Rescue (SAR)

SAR missions are usually conducted when accidents or other incidents occur within maritime areas. These situations might involve, for example, downed aircraft or disabled vessels or persons who are incapable of returning to port (Ashpari 2012). In order to carry out SAR missions, an OPV should have sufficient speed, range, radar and other needed equipment and personnel to locate and rescue victims and to deliver medical attention, as needed.

The relevant NPS student thesis discussed the methodology in building an Excel-based model consistent with the MBSE design concept that considered the effect of carrying more helicopters, unmanned aerial vehicles, and the effect on a ship’s speed. Emphasis was placed on honing the tool through meta-modeling, so as to increase its level predictability. The tool’s reliability increased as noise factors, such as visibility and wind direction were eliminated or controlled, most notably achieving an R Square factor of 0.922 (Ashpari 2012).

### 2. Maritime Interdiction Operations (MIO)

MIO is described in the *Joint Publication 3-32* as "efforts to monitor, query, and board merchant vessels in international waters to enforce sanctions against other nations such as those in support of United Nations Security Council resolutions and/or prevent the transport of restricted goods. MIO lines of authority should be streamlined, and must be clearly understood by all forces involved in the conduct of the mission" (Joint Chiefs of Staff 2013, xiv). As in the case of a SAR focused OPV, an OPV engaged in MIO should have sufficient speed, range, and well as boarding equipment and weaponry to accomplish the mission, as the role of naval forces in a MIO mission is to "employ missiles, munitions, torpedoes, and mines" (Joint Chiefs of Staff 1997, vii).

### 3. Anti-Surface Warfare (ASuW)

ASuW missions are defensive in nature and require the OPV to thwart attacks from the air, surface waters, and subsurface waters. Such threats may come from aircraft, land-based launchers, surface ships, or submarines (McKeown 2012). A common form of attack is the small boat swarm attack, such as made on the *USS Cole* (DDG 67) in 2000, and the cargo ship, *MV Maersk Alabama*, in 2009. As in the case of an OPV outfitted for SAR or MIO, an OPV engaged in ASuW should have sufficient speed, range, and, of course, the equipment and weaponry, such as radar, sonar, large caliber guns, canons, and missiles needed to defend itself or others.

The relevant NPS student thesis that studied the use of OPVs for ASuW mission also employed MANA, as well as John's MacIntosh Model (JMP) and the tool developed by our Italian colleagues, Orrizonte Sistemi Navali (OSN). The focus of the thesis was to test the reliability of operational evaluation models and ship synthesis models to help decision makers understand trade-offs concerning naval architecture. Various models were built based upon multiple scenarios involving vessel capabilities, most notably speed, length, and height, as well as the capabilities of offensive and defensive weaponry, particularly against small boat swarm attacks. Similar to the SAR and MIO testing, statistical analysis suggested that MANA can be useful in predicting the effectiveness of OPVs in ASuW; 98% of all variations could be explained (McKeown 2012).

## D. PRIMARY RESEARCH QUESTION

The primary question addressed by this thesis is can a ship system synthesis model be designed for an OPV that links ship design parameters with a set of operational requirements that are generated from operational modeling of MIO, SAR, and ASuW missions?

The approach taken to answer these questions begins with a discussion of the traditional methodology in designing ships and what enhancements are desired to improve on such methodology. MBSE is discussed, as are the criteria of measures of effectiveness (MOEs) and measures of performance (MOPs). Testing is performed through synthesis to demonstrate how a ship's naval design can be linked with systems designs for certain missions, such as MIO, SAR, and ASuW. Subsequent research will allow the results of this thesis to be inputted to a dynamic dashboard in order to enable designers and decision makers to determine feasibility based upon the data collected and the synthesis performed.

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# II. METHODOLOGY

## A. APPLYING MBSE TO IMPROVING SHIP DESIGN

To reiterate, MBSE has been described as:

> …the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. In particular, MBSE is expected to replace the document-centric approach that has been practiced by systems engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of systems engineering processes (INCOSE 2007, 15).

The focus for NPS researchers is to apply MBSE early in the acquisition life cycle to aid in decision making. To achieve this, the overall approach is to address the following three aspects:

> (1) Use architectural MBSE software tools (like CORE) to establish a common language for the system engineering team to define a central data source that will support system architecture development; (2) Use external models to assess the performance of different functional/physical architectures derived from the MBSE software tool. System engineers have been using models forever; we want to know how they can directly populate the performance data derived from the MBSE software tool; and (3) Develop decision support "dashboards" that can illuminate the trade space and facilitate analysis (Paulo 2012, slide 5).

The NPS design concept using MBSE is illustrated in Figure 2.

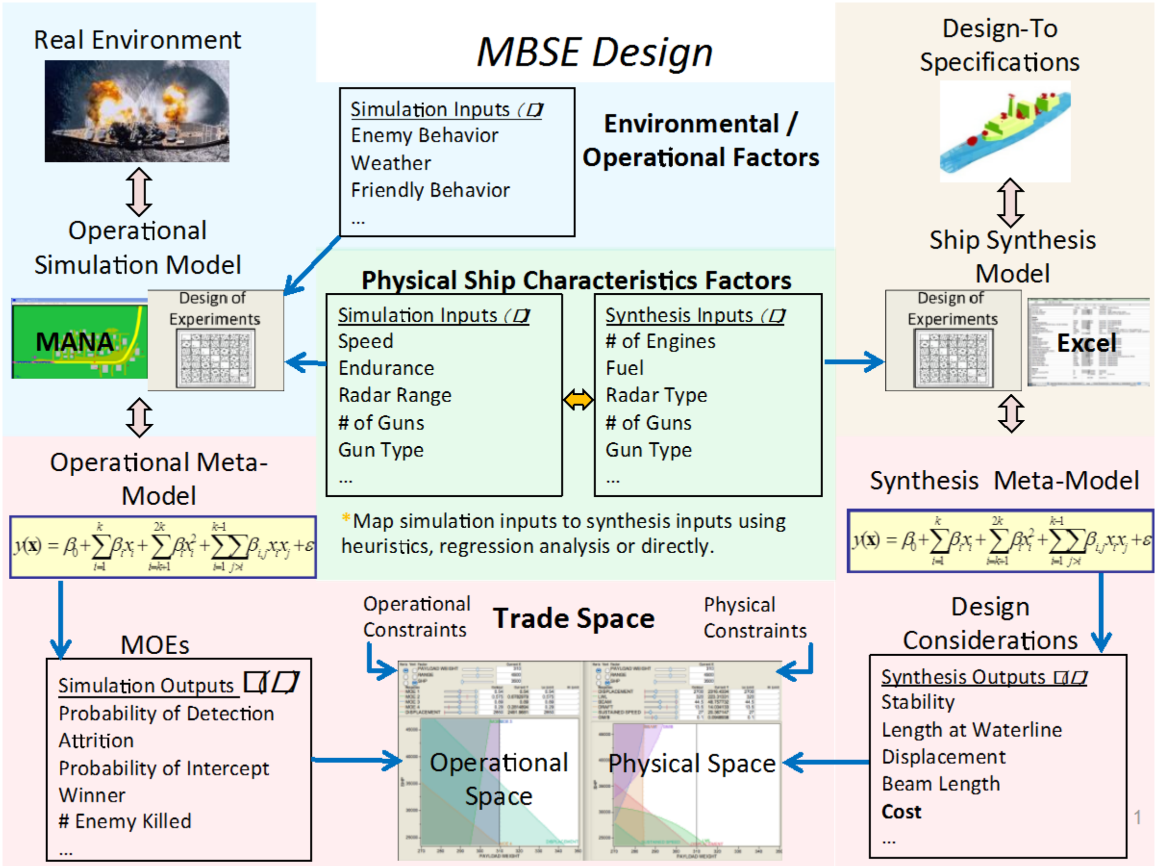



Figure 2. MBSE Design for PRONTO/ASNET Project (MacCalman 2013)

The left section of Figure 2 starts with the real environment in which operational simulation models are constructed through techniques such as agent-based modeling (e.g., Map Aware Non-Uniform Automata [MANA]), design of experiments [DOE]) and simulated by inputting a wide range of environmental, operational and physical factors to show the relationship between the MOEs listed and the physical ship characteristics.

The middle section of Figure 2 is concerned with visualization of results from operational and synthesis models. Analysis of the trade spaces defined in those models should allow a ship designer to control ship design parameters based simultaneous visualization of the operational and physical trade spaces.

The right section of Figure 2 models the feasibility (and infeasibility) of the various ship configurations through physical constraints to yield synthesis outputs. The box labeled “Synthesis Outputs y(x),” which appears at the lower right-hand corner of

Figure 2 is the focus of this thesis. The expectation is that this thesis will add to the knowledge required to link the operational space with the physical space, as depicted therein. That subject matter is discussed in Chapter III.

## B. DASHBOARD—ANSWERING "WHAT IF" QUESTIONS

A significant aspect of NPS' adaptation of MBSE may be its ability to use a dynamic dashboard developed by the NPS research team. The dashboard is focused on the simultaneous presentation of operational and physical trade spaces through the use of contour profilers. The dashboard immediately illustrates the effects of changes in design as these contour profilers are adjusted. The dashboard answers most "what if" questions by enabling the user to immediately see the consequences when the profilers are adjusted. In general, the initial step in the MBSE procedure calls for entering the proposed design parameters into a computer modeling system. Then, modifications for mission-specific operational systems would be inputted and synthesized through the dashboard. The dashboard presentation mechanism allows for dynamic visualization of polynomial meta-model functions. This allows for rapid examination of the impact of proposed design changes, so that the user may immediately visualize the end designs. As such, if the proposed design change were to cause the vessel configurations to fall outside of the range of acceptability, then the designer would know to eliminate the design from further consideration. However, the dashboard would also give the designer the ability to adjust the design parameters, possibly to bring the design back into the range of acceptability. Likewise, the usefulness of the dashboard may be even broader in that it may allow the designer instantly to determine if characteristics of other types of ships may be imported to ship designs already under consideration.

For example, if the additional weight caused by the inclusion of a helicopter flight deck could render the ship incapable of meeting its minimum speed requirement, then eliminate that particular ship configuration from further consideration. However, if through trade-offs, such as the adding a more powerful propulsion system or removal of a missile system that would not typically be used in the particular patrol area, the resulting reduction may then accommodate the needed flight deck. The dashboard should allow the designer to make such determinations right away. A depiction of the dashboard is follows in Figure 3.

The previous thesis work, described in Chapter I, resulted in meta-models that are included in the operational trade space in Figure 2 that forms the NPS team's dashboard. The work of this thesis is intended to show what is realistic (and unrealistic) in the physical space by developing a meta-model that can be incorporated into the dashboard.

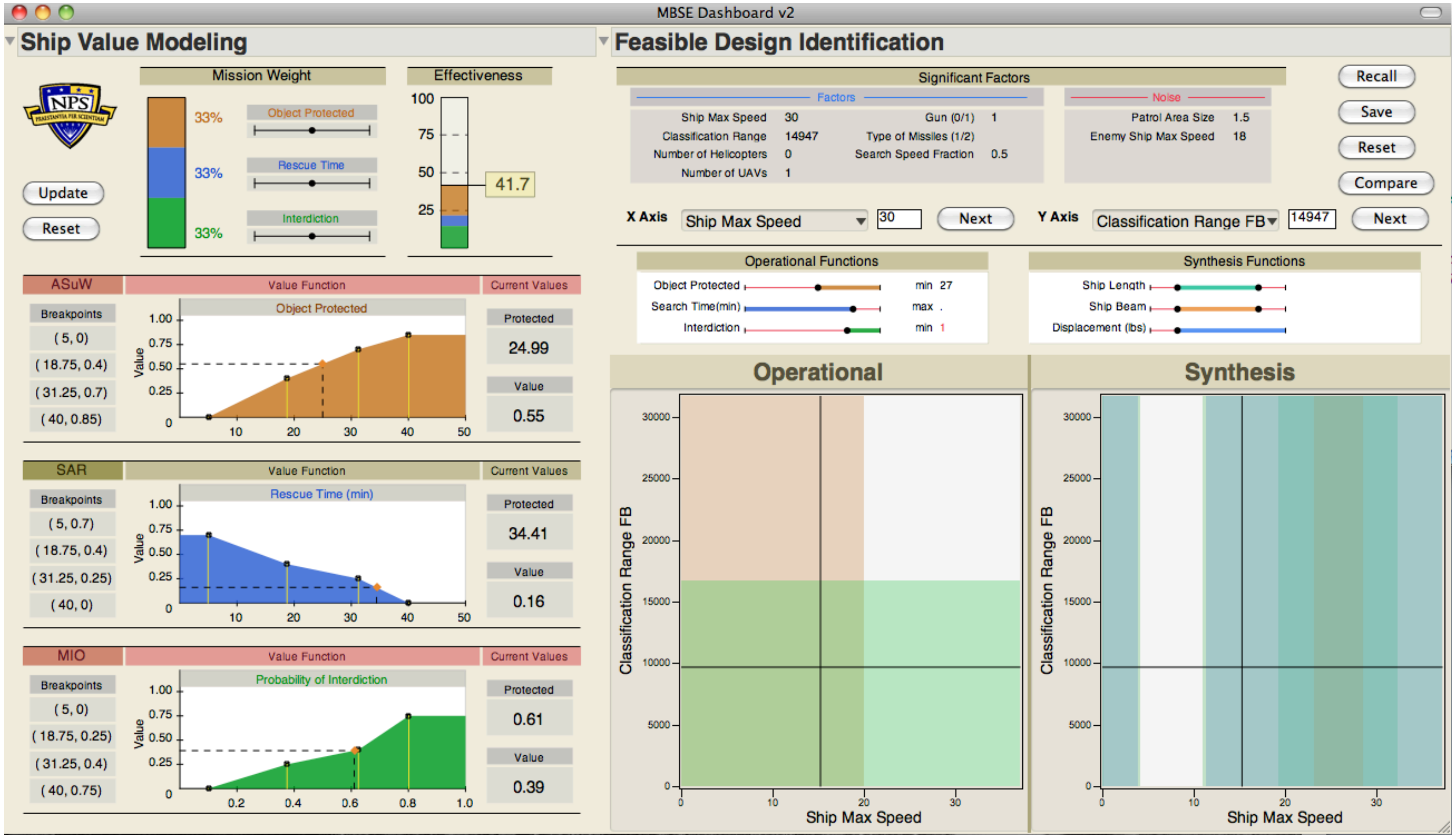



Figure 3. NPS Dashboard for PRONTO/ASNET Project (Beery and Roeder 2012; Lineberry 2012)

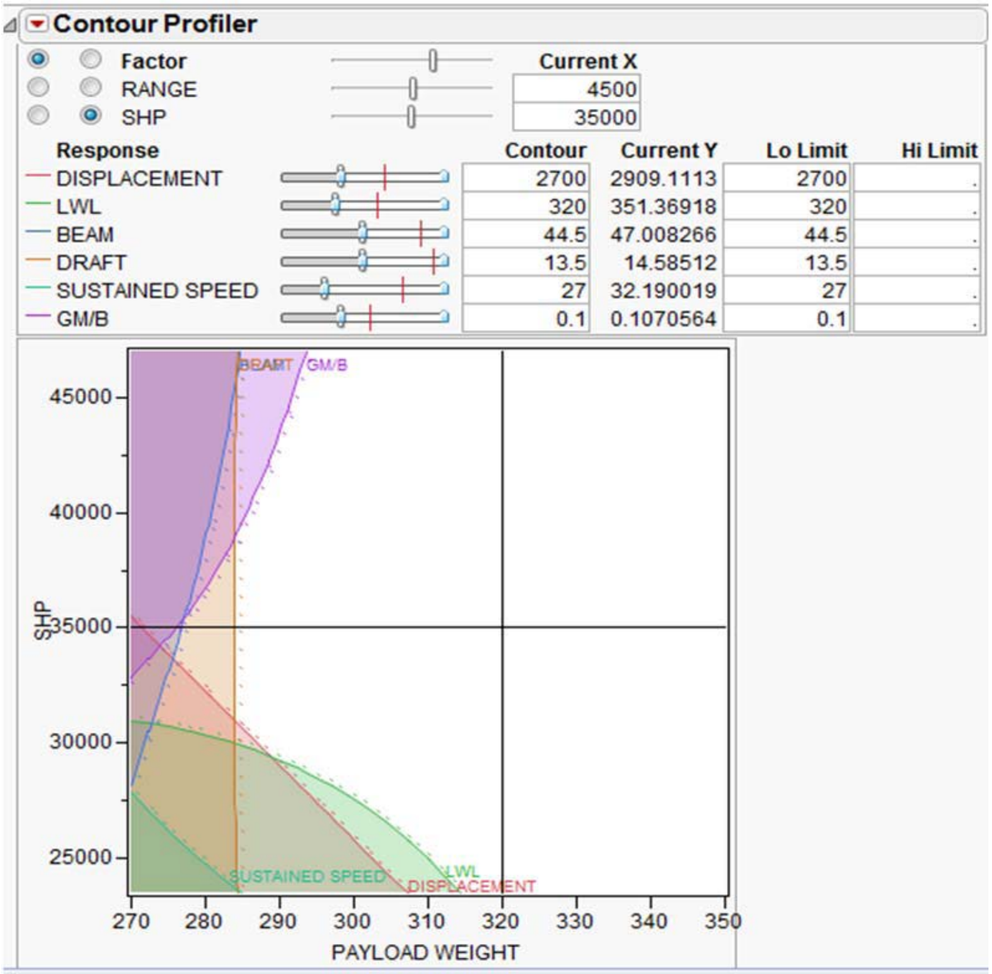



Figure 4. NPS Dashboard—Contour Profilers (Gaitan 2011)

## C. ESTABLISHING MOPs AND MOEs

Understanding the difference between MOPs and MOEs is important to better understand the NPS design concept using MBSE (Fox, 2011). Simply stated, "a MOP describes what a system does on an easily measurable scale (e.g., speed, firing range, radar range et cetera), while a MOE attempts to measure how a system performs in the external environment towards achieving a desired result" (e.g., a kill ratio) (Fox 2011, 8).

Applying the foregoing explanation to Figures 2, 3, and 4, an initial step would call for establishing such factors as MOPs (e.g., a ship's capability such as top speed, maximum range, and maximum cargo carrying ability). Then, as suggested by

(MacCalman 2013) MOEs can be set MOEs can be set in meta-models to test the dependence against the MOPs. By doing so, the analyst can readily adjust the contour profilers to account for changes in data to determine if the design is suitable for the ship's intended use. Once that determination is made, then the user can decide either to reject the design or to modify the parameters against the MOEs to see if the modifications might bring the design back into the range of acceptability.

Examples of MOEs for the three types of missions follow:

- SAR: The measure of how effective the vessel is in a search and rescue mission might be how quickly the task is completed against a predetermined time frame (e.g., probability of reaching the victim or target within a certain period of time for survivability.)
- MIO: The measure of how effective the vessel is in an interdiction effort might be the percentage of pirate vessels that are captured or sunk in an effort to protect cargo vessels from capture by the pirates.)
- ASuW: The measure of how effective the vessel is in an anti-surface attack, such as a small boat swarm attack, might be the probability of protecting the victim vessel from an incoming missile or torpedo attack (Paulo 2012, slide 17).

## D. TRADITIONAL AND RECENT TOOLS FOR MODELING/ SYNTHESIZING

This section of the thesis briefly surveys some of the more traditional tools that have been used for ship design modeling and synthesizing. It appears that there is no tool that captures all of the pluses and minuses that exist or that arise in the design process, so any one of these tools or others may be suitable, depending upon the user's familiarity with the tool or the type of vessel design that is under consideration. An overview of these tools follow:

### 1. Advanced Ship and Submarine Evaluation Tool

Advanced Ship and Submarine Evaluation Tool (ASSET) is a software program that has been in service as a traditional tool, and it is intended for use by trained naval architects and engineers. Training and/or consulting services by Naval Surface Warfare Center Carderock Division (NSWCCD) is strongly recommended (Kassel, Cooper and

McKenna 2010). ASSET is typically used to predict characteristics of a ship's performance based upon the requirements of the mission (Choi 2009). The inputs considered for synthesis effort considers hull design, ship resistance, propulsion system, displacement and weight among other variables. ASSET, however, does not consider the topside deck layout, as other programs are used for those calculations. An advantage of ASSET is that it can model a military vessel's displacement, ranging from about 4,000 to 10,000 tons from a few number of naval design variables (Choi 2009; Fox 2011). Moreover, in a personal interview with Daniel Billingsley, a career engineer at NAVSEA, he highlighted that since the inception of ASSET in the mid-1970s, the algorithms used for design have been validated by real ships designed for and used by the U.S. Navy (personal communication December 10, 2012). Since most of the OPV numbers in Table 1 reflect displacement of less than 4,000 tons, and most of the historical ship data in ASSET begin with displacement of around 4,000 tons, there is a gap that does not account for OPV modeling. Sensitivity analysis can be used to estimate OPV measurements to close this gap, however, this would not allow ASSET to use its validated database of designs. In addition, any design integration is lost beyond the concept phase and attempting to regain design integration by manually preparing input data accounts for time, cost and errors in its analysis (Kassel, Cooper and McKenna 2010, 2). A sample illustration of ASSET is shown in Figure 5.

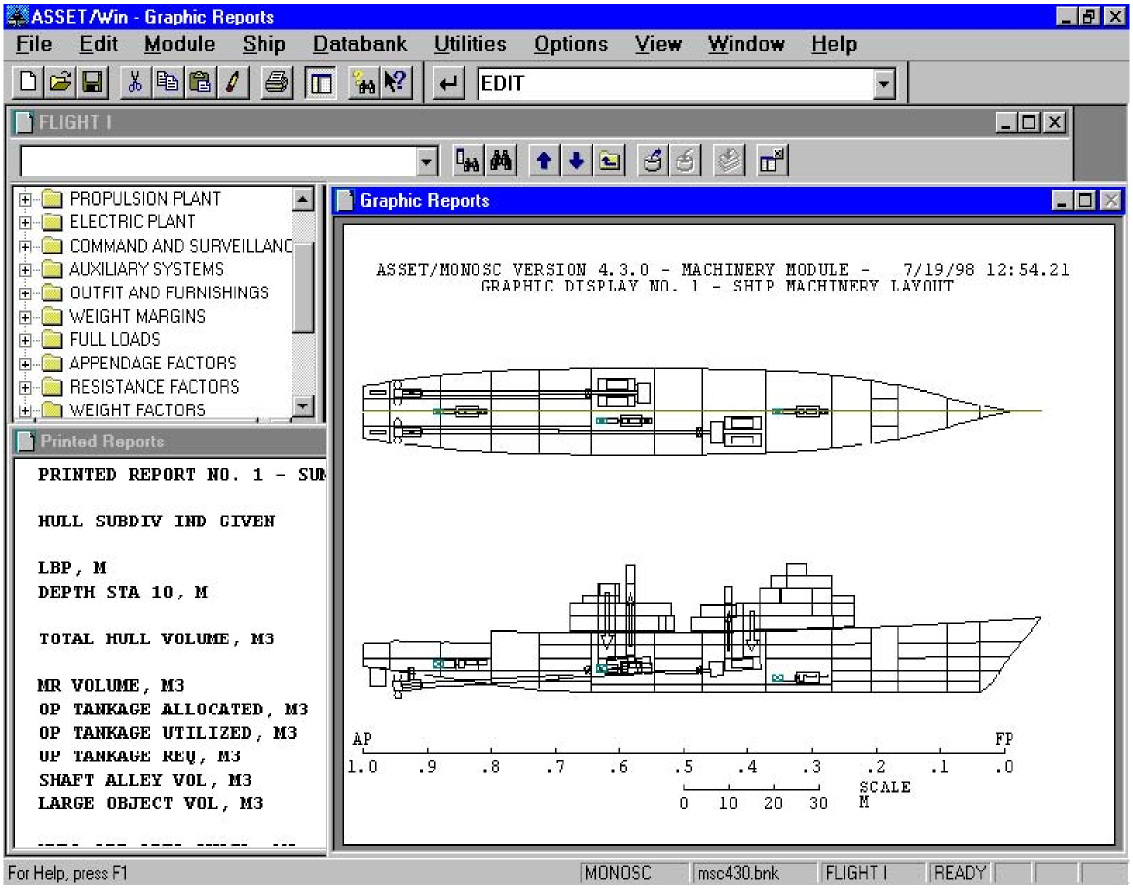



Figure 5. ASSET Overview (Choi 2009; Koleser 2005)

### 2. Leading Edge Architecting for Prototyping Systems (LEAPS)

Since the mid-1990s, LEAPS has been in service as a way to integrate many analysis tools into a common environment. It relies on ASSET and serves to accelerate the modeling process, while also presenting a more comprehensive model (Kerns 2011). It would seem appropriate that if ASSET is used as a tool for synthesizing, then LEAPS should be used to determine if a more robust model would result and thus attempts to close the design gap. Nevertheless, there are still gaps unmapped in LEAPS to fulfill its integrated approach (Kassel, Cooper and McKenna 2010, 3).

### 3. Performance-Based Design Continuum (PBDC)

PBDC has been in service as a traditional tool, and it supplements LEAPS in that it broadens the modeling beyond the ship design phase. It extends the modeling into the ship's construction, milestone test stages, and even into the life cycle phases (Fox 2011).

### 4. Rapid Ship Design Environment (RSDE)

RSDE is a recently developed tool that allows naval architects and design engineers to explore the design space using design of experiments (DOE). It can be used with ASSET and LEAPS, as well as John's Macintosh Project, a statistical analysis software program which is commonly referred to as JMP. RSDE is capable of synthesizing ship design with operational characteristics during the early stages of ship design (C. A. Whitcomb, personal communication, January 7, 2013).

### 5. Integrated Hydrodynamic Design Environment (IHDE)

IHDE also is a tool developed around 2008 that integrates hull design and permits the designer to evaluate hydrodynamic performance, including resistance. It too is used in a LEAPS database from ASSET (C.A. Whitcomb, personal communication, January 7, 2013).

This author is not rejecting or discouraging the use of these tools. Rather, this author has sought to find a tool that could easily be used early on to eliminate proposed models that have a strong likelihood of being infeasible, so as to not waste the designer's time and stakeholder's monies in the initial design stages. Then, any one or none of the aforementioned tools or other tools can be used in the synthesizing and modeling stages to decide whether the remaining designs should be pursued further. This thesis suggests that the five-parameter method may be useful in the initial stages of design testing so as to reduce the learning curve associated with learning how to use traditional modeling and synthesizing tools.

## E. PROPOSED TOOL—MCKESSON'S FIVE-PARAMETER METHOD

In two published articles, the first titled, "A Parametric Method for Characterizing the Design Space of High Speed Cargo Ships" (McKesson 2006), and the second titled, "The Utility of Very Simple Models for Very Complex Systems" (McKesson 2011), the author discusses his easy-to-use "method that offers a very rapid tool for determining if a proposed design is worth pursuing further" (McKesson 2006, 1). After reviewing the articles and performing some preliminary tests, Dr. McKesson's tool was examined closely to determine if it might be useful in applying the MBSE approach to ship design as part of this thesis. The five-parameter method is discussed further in Chapter III.

## F. SOURCES OF DATE FOR TESTING—JANE'S FIGHTING SHIPS

The data for OPVs that was used for testing purposes comes from *Jane's Fighting Ships*. *Jane's* is a reference source of worldwide ship data updated annually and is commonly used by ship designers and naval architects. For purposes of developing this thesis methodology data from the year 2012 have been used, since any revisions thereto have likely been made. Of course, users can import more current data as it becomes available.

The data extracted from *Jane*'s for testing and analysis include the type/class of vessel, the type and number of engines and their horsepower, and the speed and displacement capabilities. See Table 1.

Table 1. Selected Data (From *Jane's Fighting Ships*, 2012)

| Nation | Ship Class | No. Engines | HP per Engine | Installed Power (hp) (Eng.xHP) | Speed (knots) | Displacement (lbs) (full load) |
|---|---|---|---|---|---|---|
| Russian Federation | Komandor class | 2 | 7020 | 14040 | 20 | 5442200 |
| US & Philippine | Cyclone class | 4 | 13400 | 53600 | 35 | 848800 |
| US | National Security Cutter | 4 | 9655 | 38620 | 28 | 9211000 |
| US | WMEC Famous class cutter | 2 | 7290 | 14580 | 19.5 | 4012400 |
| US | Hamilton Class | 2 | 36000 | 72000 | 29 | 7392000 |
| US | WMEC Reliance class cutter | 2 | 5000 | 10000 | 18 | 2248800 |
| Montenegro | Kotor class | 1 | 18000 | 18000 | 27 | 4188800 |
| Taiwan | PSO | 2 | 19850 | 39700 | 24 | 4640800 |
| Spain | Meteoro class | 2 | 12000 | 24000 | 20.5 | 6261200 |
| Colombia | PSO | 2 | 10940 | 21880 | 20 | 3798600 |
| India | Vikram class | 2 | 12800 | 25600 | 22 | 2742600 |
| United Kingdom | River Class | 2 | 11063 | 22126 | 20 | 3807400 |
| United kingdom | Modified River Class | 2 | 11063 | 22126 | 20 | 4138000 |
| Spain | Alboran class | 1 | 2400 | 2400 | 13 | 4398200 |
| Portugal | Viana Do Castelo | 2 | 10460 | 20920 | 20 | 4118200 |
| Malta | Diciotti class | 2 | 6335 | 12670 | 23 | 879600 |
| Spain | Serviola class | 2 | 7500 | 15000 | 19 | 2568400 |
| Malaysia | Langkawi class | 2 | 12720 | 25440 | 22 | 2912400 |
| Turkey | Milgem class | 2 | 11580 | 23160 | 29 | 4479800 |
| France | Florẻal class | 4 | 8820 | 35280 | 20 | 6607200 |
| Italy | Cassiopea class | 2 | 7940 | 15880 | 20 | 3304800 |
| US | Asheville | 1 | 12500 | 12500 | 35 | 527000 |
| US | Sentinel | 2 | 5760 | 11520 | 28 | 791400 |
| US | Island | 2 | 6246 | 12492 | 29 | 377000 |
| Latvia | Valpas | 1 | 2000 | 2000 | 15 | 1221400 |
| Iraq | OPV (PSO) | 2 | 6300 | 12600 | 16 | 3086400 |
| Finland | Improved Tursas class | 2 | 3808 | 7616 | 15 | 2464800 |
| Finland | Tursas class | 2 | 4360 | 8720 | 14 | 2799800 |
| India | Rani Abbakka class | 3 | 10842 | 32526 | 34 | 615000 |
| Venezuela | Constitución class | 2 | 6000 | 12000 | 31 | 381400 |
| Sri Lanka | Jayesagara Class | 2 | 2180 | 4360 | 15 | 738600 |
| Taiwan | WPSO | 2 | 19850 | 39700 | 30 | 1567400 |
| Spain | Pescalonso class | 1 | 2460 | 2460 | 12 | 4706800 |

# III. DEVELOPMENT OF PHYSICAL (SYNTHESIS) MODEL

As discussed in the previous chapter, the focus of this thesis is in the development of the physical model. From Figure 2, the physical model, or ship synthesis model, is a meta-model that links design considerations (sometimes called operational factors, or possibly operational requirements) to ship design factors. The origin of an appropriate meta-model is a regression model that establishes a potential relationship between the input factors (design considerations) and the design factors (see Figure 6). For the OPV, the development of appropriate, specific design considerations and design factors are discussed later in this chapter.

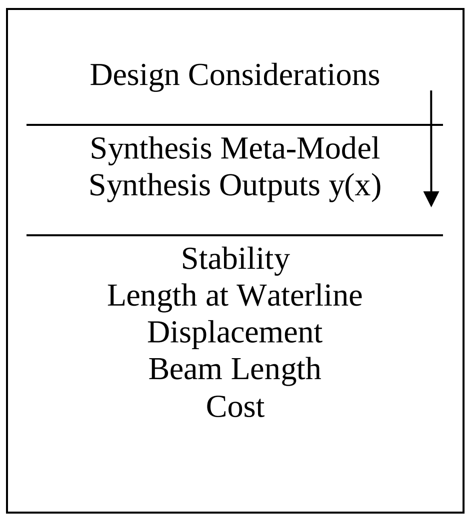



Figure 6. MBSE Design (PRONTO/ASNET)—Synthesizing Designs

The purpose of this research is to demonstrate a linkage between a synthesized, physical design and the operational space (i.e., trade space needed to clearly visualize operational success in SAR, MIO and ASuW missions). Stated differently, traditional naval architecture concentrates on metrics such as range, displacement, and speed. On the other hand, military-minded engineers are more concerned with designing space that can best accommodate the systems needed to accomplish the military mission, such as guns, missiles, radar, and helicopter capabilities.

The initial step toward devising a method of linking is to identify which basic parameters are desired when designing the physical space. The overall goal for the MBSE concept may be to design a ship, for example in terms of the MIO mission, that can intercept 90% of drug boats. Such a ship requires a speed of “x” knots. A speed of “x” requires a displacement of “y” LTs. This MBSE concept is in contrast to the traditional ship design paradigm where the overall goal may be to design a ship that can attain a minimum speed of “x” knots, a maximum displacement of “y” LTs, and a range of, say, 3000 nautical miles. The challenge of the traditional ship design paradigm is to identify those characteristics of a ship that can achieve those goals. By attaining the MBSE ship design, the stakeholder hopes to achieve a less costly but mission-effective system as opposed to a traditional ship design that may be more costly and not be a mission-effective system.

The next step would be to identify characteristics needed for military missions, such as SAR, MIO, and ASuW, and then to look for common characteristics with physical space designs. While speed, range, and displacement could impact a ship’s performance, the more important question is what are the trade-offs in space design and speed range, and displacement when adding or deleting weapons, helicopters, radar, or other military systems.

## A. CHOICE OF TOOL FOR TESTING—FIVE-PARAMETER METHOD

As is discussed in Chapter II, there are several potential solutions for selecting an appropriate model. However, for the purpose of this thesis, the tool of choice for testing and analysis is the five-parameter method. The tool was created for determining whether a particular ship design might satisfy the minimum goals for a high-speed cargo ship (McKesson 2006 & 2011). However, the question arose whether the tool would be used for designing a military ship, such as an OPV. Dr. McKesson, the designer of this model, responded favorably to this question in his personal email message, dated February 25, 2013, to the author, Dr. McKesson stated:

> “[y]es, the very simple method would work fine for an OPV. You need to simply use the military mission package ‘payload weight’ to replace my ‘cargo weight’ in the merchant ship case. [emphasis added] Having done

so, don't mistakenly think that the model is giving a measure of merit: It will give some ship characteristics (e.g., displacement) but it 'knows nothing' about the military usefulness of the given 'cargo.' A 100-tonne mission package might be a more potent warship than a 200 tonne package."

## B. BEFORE TESTING—KNOW THE NOMENCLATURE

The following nomenclature has been selected from Dr. McKesson as pertinent for explaining the application of his tool to this thesis. A definition of each is included: (McKesson 2011, 5):

- D Drag: This is the resistance on a ship from all sources which determines how fast a ship can move for a given power input. (Makiharju 2008); (Maritime Systems).
- EHP Effective Horsepower: This is the amount of power that must be delivered in order to move the ship at a design speed. Effective horsepower is not the same as real engine horsepower, because of losses in the transmission, and most importantly, at the propeller. In practice, real horsepower must be approximately twice EHP in order for the ship to move at the design speed (Maritime Center).
- $Fn_{vol}$ Volumetric Froude number: $Fn_{vol} = V/\sqrt{[g(\Delta_{vol})^{1/3}]}$ The Froude number relates the speed of a vessel to its length by a formula that considers the vessel's speed, length and the acceleration due to gravity. At a low Froude number (low speed-to-length ratios), the wave resistance is low and the viscous resistance dominates. As speed (Froude number or F) increases, wave resistance becomes a higher percentage of total resistance – until at the critical or "hump speed," wave resistance exceeds viscous resistance. This large increase occurs when F = 0.4, and is maximum at F = 0.5. Conventional ships always operate at Froude numbers below this primary hump speed. To achieve high speed, naval architects design their ships to operate below the F = 0.4 threshold by incorporating long lengths. Only Navy ships with high installed-propulsion power can operate at a Froude number above 0.4 (Global Security.Org. 2013).
- g Gravitational Constant (9.8 $m/s^2$): Gravitational potential energy is the energy that an object possesses because of its position in a gravitational field. The most common use of gravitational potential energy is for an object near the surface of the Earth where the gravitational acceleration can be assumed to be constant at about 9.8 $m/s^2$ (Nave 2013).
- L Lift: This is the force that pushes as ship upward due to buoyancy; based upon Archimedes' Principle, the weight of the fluid that is displaced is used to calculate buoyancy (Gillmer 1982).
- LT Long Tons: This term is often used when discussing the weight of

a ship or its cargo. It originated from the British system of measurements. A long ton is equivalent to 2,240 lbs. By comparison, the term short ton originated from the American system of measurements, and a short ton is equivalent to 2,000 lbs. (Gillmer 1982).

- OPC Overall Propulsive Coefficient: OPC is defined as the ratio of the "Effective Power" (EP) divided by the total installed Shaft Horsepower (SHP). It serves as a means by which to rate the efficiency of the propulsion system. The resulting OPC ratio for a propeller driven vessel is typically 0.6; For comparison purposes, the OPC ratio for a water jet driven vessel is typically 0.7 (McKesson 2006).
- SFC Specific Fuel Consumption: SFC is the overall fuel consumption of the machinery on a specific or per-horsepower-hour basis. Engines are rated, and this metric is obtainable from engine catalogs. However, it is usually monitored by a ship operator as well. A SFC of 0.40 lbs./hp is reasonable and typical (McKesson 2006).
- SHP Shaft Horsepower: SHP is the power delivered to the propeller shaft. It can be measured or estimated from the indicated horsepower and a standard figure for the losses in the transmission (typical figures are around 10%) (Gillmer 1982).
- V Ship speed in meters per second: 1 nautical knot per hour = 0.5144 meters per second; 1 mile per hour = 0.4470 meters per second (Gillmer 1982).
- Vk Ship speed in knots: 1 mile per hour = 0.8690 knots per hour (Gillmer 1982).
- $\Delta_{vol}$ Displaced volume in cubic meters: 1 ton (water) is equal to 1.01832416 cubic meters ($m^3$); 1 cubic meter ($m^3$) is equal to 0.9820 tons (water).

## C. OVERVIEW OF FIVE—PARAMETER METHOD

Before providing an overview of the five-parameter method, it may be helpful to understand why it includes certain particular parameters. The method is an expansion of the studies C. Kennell and M. Templeman regarding ship design analysis and assessment (McKesson 2011). Those studies revealed that "it is possible to predict the characteristics that a ship will have from a very sparse set of early design requirements" (McKesson 2011, 735). Those design requirements included the five parameters in various forms, but it was Dr. McKesson who formalized them as collective components of his tool. Since those parameters served as sufficient predictors, there appeared to be no need to expand the number of parameters, as the intended use was to develop a method that would be "a very rapid tool for determining if a proposed design is worth pursuing further" (McKesson 2006).

Further, it is important to remember that the five-parameter method is not intended to be a substitute for traditional tools, such as ASSET or LEAPS; rather, it is intended to align with them (McKesson 2006). This author envisions the five-parameter method as a rudimentary tool to be used by a designer to quickly assess whether a proposed design should be eliminated from further consideration. Elimination would likely occur because the resulting ship characteristics would be far outside the realm of acceptability. Then, traditional tools would be used to further test those designs which the five-parameter tool has approved for further consideration. As such, the five-parameter tool should spare the inspector from possibly time-consuming and thus costly testing of designs that are infeasible from the outset. With this in mind, this tool may be helpful in the initial stage of testing. A brief overview of each parameter follows.

### 1. Lift/Drag Ratio (L/D Ratio)

The amount of power required to move a ship and its payload, depends, in part, on the forces of lift and drag. These forces are briefly described above. Lift and drag work against one another, as lift pushes the ship upward due to buoyancy, while drag pulls the ship down due to gravity. The L/D ratio is the metric used to measure the extent that each of these forces work; the greater the ratio, the more the buoyancy than drag, thereby the lower the resistance. Of course, the less resistance, the less power that is needed to propel the ship. The term lift to drag, which was borrowed from the airspace industry, is the same as the familiar weight to drag ratio for ordinary displacement ships. A large ratio designates a ship that carries a large displacement for a given drag, or conversely experiences smaller drag for a given weight. Therefore, larger values indicate a more efficient design as far as this coefficient is concerned.

After the L/D ratio is identified for the ships whose design is under consideration, it is plotted against the volumetric Froude number of each ship, so that the most efficient combination of L/D ratio can be identified. This graph is referred to as the "Best Practices

Curve," and it is depicted in Figure 7 that follows. It should be noted that the ships included were cargo ships, and the L/D ratio of 17.28 is identified as the most efficient combination. As a point of comparison, Figure 8 uses the same approach for identifying the most efficient combination of L/D ratio and volumetric Froude number, but for a combat ship, and that L/D ratio is 18.01. The higher L/D ratio equates to less resistance and therefore less power to propel the ship forward. This higher L/D ratio may be explained in part due to a hull which is designed for less wetted surface, thereby reducing resistance. The L/D ratio, of course, will depend on the particular ship designs included in the data chosen.

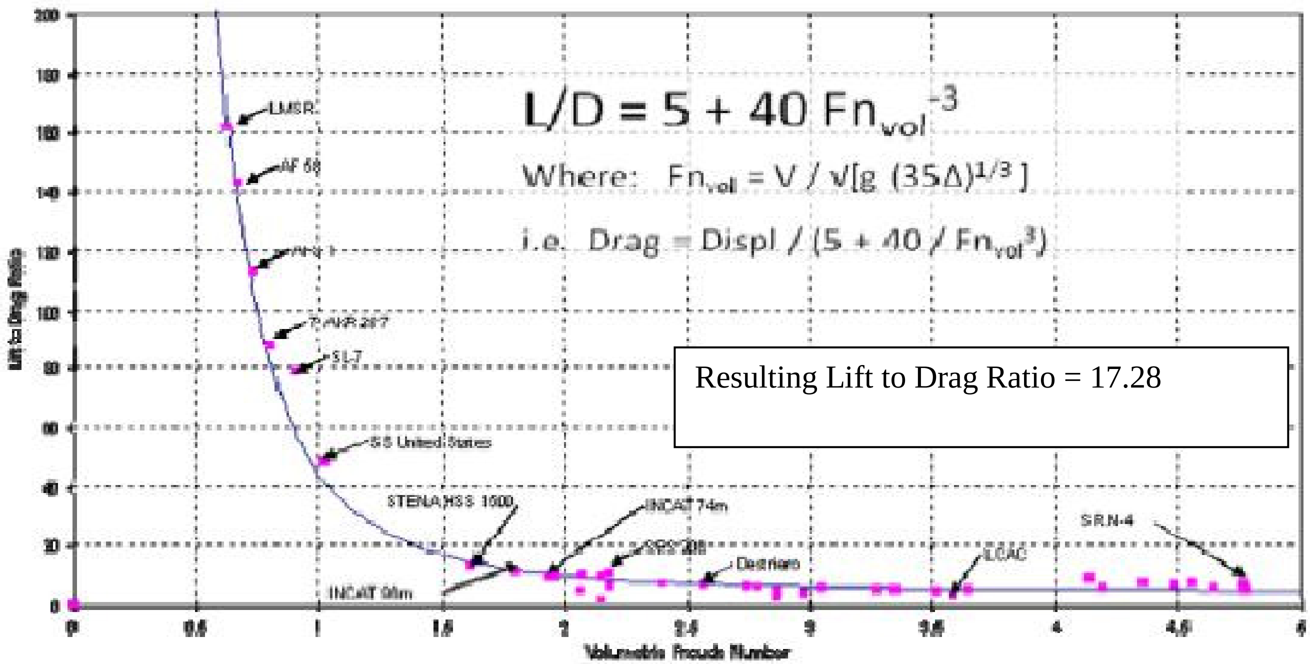



Figure 7. McKesson's Lift/Drag Ratio (Cargo Ship) [McKesson 2006]

### 2. Overall Propulsion Coefficient (OPC)

The Overall Propulsive Coefficient (OPC) is the ratio of the power utilized by the ship, to the power that is installed on the ship. The power that is utilized by the ship is equal to the drag of the ship times its speed. In this model, a constant value for OPC is assumed, that is selectable by the user. In general, the OPC is a function of ship, operations, as well as propeller characteristics. As in the case of the L/D ratio, the greater the resulting OPC, the greater the efficiency of the system.

### 3. Specific Fuel Consumption (SFC)

The specific fuel consumption (SFC) is the weight of fuel per unit time per unit power. A lower number designates higher fuel efficiency. The primary source for this is the burn rate of the main propulsion engines, even though auxiliaries and generators are typically considered. The SFC varies throughout the operation range of the design. It also depends strongly on the type of propulsion plant used. Diesel engines have lower SFC and that remains relatively constant throughout their power range. Gas turbines have a higher SFC and are efficient at high power settings. At lower power settings, their SFC is significantly higher.

### 4. Weight of the Power

The weight of the power means the weight of the propulsion plant, including engines and the propulsors, plus, the weight of the fuel, as stated in pounds per horsepower (HP) (McKesson 2011). Dr. McKesson calculates and uses eight to 10 lbs. per HP as a “real world” number. This is of course dependent on the type of propulsion plant used. It is treated in the model as a variable selectable by the user. The lower the weight of the power, the more efficient the system.

### 5. Weight Capacity of Cargo Carrying Capacity

Dr. McKesson suggests that the weight of cargo carriage capacity be thought of as the weight of the shopping bag into which the cargo can be placed. He mentions that data does exist for actual ships, but for simplicity purposes chooses to use a “Cargo Carriage

Multiplier” of 2 lbs., per lb. of cargo (McKesson 2011). It should be emphasized that is highly related to the type of ship and other considerations such as protection or survivability. In general, cargo ships have a lower number, and naval vessels, depending on design and requirements, have a higher number.

## D. FORMULAS OR ASSUMED VALUES USED FOR TESTING

The formulas and assumed values below are used by this author to apply and extend the five-parameter methodology to studies of this thesis. Where it appears necessary, a brief explanation is included (McKesson 2011):

### 1. Parameter 1: Lift/Drag Ratio (calculated value)

$$L/D \text{ (cargo ships)} = (5+40/Fn_{vol}^{-3.0})$$

$$L/D \text{ (military ships)} = (2.82+15.53/Fn_{vol}^{-3.4})$$

Notably, the formulas for the L/D ratio differ in two respects: (1) the lower and upper limits for wave resistance of 5 and 40, respectively, for typical cargo ships; and 2.82 and 15.53 for typical combat ships; and (2) the coefficients for the volumetric Froude numbers for -3.0 for cargo ships, and -3.4 for military ship. The rationale behind these numbers is that the hull of a cargo ship is designed to maximize its cargo-carrying ability, and therefore typically has a greater wetted surface, thereby causing more wave resistance, so as to give rise to the higher factors (i.e., 5+40). On the other hand, the hull of a combat ship is designed to maximize its speed, so it is likely to have less of a wetted surface, thereby causing less of a wetted surface, so as to permit lower factors (2.82+15.53). Consistent with this thinking, the coefficient for cargo ship’s Froude number moves in more of a positive direction to reflect the greater water resistance expected for the cargo vessel (i.e., -3.4 for combat vessel, versus -3.0 for cargo vessels. (McKesson 2006, as to cargo ships; F. Papoulis personal communication on July 25, 2013, with respect to military ships). Refer to (McKesson 2013) for a further discussion on the lower and upper limits for wave resistance of 5 and 40.

### 2. Parameter 2: Overall Propulsion Coefficient (OPC) (Assumed Value)

The weight of the fuel is comprised of the (a) propulsive efficiency of the ship, and (b) fuel efficiency of the power plant (McKesson 2011). These components are not separately described here since they are combined into a single coefficient, entitled the OPC. It is generally acceptable for ship designers to accept an OPC of 0.60 to 0.70 (Barrass, 2004, 75; McKesson 2006 and 2011).

### 3. Parameter 3: Specific Fuel Consumption (SFC) (Assumed Value)

A SFC of .40 lbs/hp-per hour is assumed here, as it is within the generally accepted range of .35 to .40 lbs/hp-per hour (McKesson 2006 and 2011).

### 4. Parameter 4: Weight of Power (Assumed Value)

Another assumed number is the weight of the power. Again, this is the prediction of the amount of power that is needed to propel the weight of a particular ship. Real world data suggests that this parameter could range from 8 to 10 lbs, per HP (McKesson 2006 and 2011).

### 5. Parameter 5: Weight of Cargo Carriage (Assumed Value)

A cargo carriage multiplier of 2 lbs/lb. of cargo is assumed here, as it is considered reasonable (McKesson 2006 and& 2011). That means that for each pound of cargo carried, the container or carriage that holds the cargo generally should be twice the weight of the cargo. The same theory is generally true for combat ships, including OPVs, and so the 2:1 ratio is accepted here (F. Papoulias, personal communication July 25, 2013).

## E. PURPOSE OF TESTING - WHAT WERE THE GOALS?

Dr. McKesson’s research intent was to determine if a methodology and a tool could be devised which could quickly determine if a proposed design might meet the requirements of ONR for high speed military sealift craft, appropriately referred to as HSSL. More specifically, ONR’s requirements that Dr. McKesson was following for HSSL called for the ship to be capable of a payload of 3,600 LT, speed of 43 knots, range of 5,000 nautical miles, and a ship whose displacement would not exceed 12,000 tons and whose length would not exceed 560 feet in length. Dr. McKesson looked into the concepts for designing a high-speed cargo vessel and identified the five parameters that became the focus of his study (McKesson 2011, 2). His conclusion was that the five-parameter approach can serve as a useful tool. The following table reflects the variables used in that study.

Table 2. Cargo Ship Metrics Used by Dr. McKesson for Five-Parameter Method

| Description of Data: | Value |
|---|---|
| Max. Full Load Displacement (LT) | 12,000 |
| Max. Speed (knots) | 43 |
| Fnvol (Froude no.) | 1.482 |
| L/D | 17.28 |
| Resistance (lbs) | 1,555,138 |
| EHP (hp) ("Effective Horsepower") | 205,126 |
| Overall Propulsive Coefficient (OPC) | 0.6 |
| Shaft Horsepower (SHP) (HP) | 341,876 |
| Specific Fuel Consumption (SFC) (lbs/hp-hr) | 0.4 |
| Range (miles) | 5,000 |
| Fuel Weight (Lbs) | 15,901,204 |
| Fuel Weight (LT) | 7,099 |
| Displacement minus Fuel (LT) | 4,901 |
| Wt of Power (lbs/hp) | 10 |
| Machinery Weight (LT) | 1,526 |
| Weight Available for Cargo & Cargo Carriage (LT) | 3,375 |
| Cargo & Carriage Multiplier (lbs/lb) | 2 |
| Cargo Carriage Weight (LT) | 2,250 |
| Cargo Load (LT) | 1,125 |
| **Summary**: | |
| Machinery Weight | 1,526 |
| Cargo Carriage Weight | 2,250 |
| Light Ship Weight (subtotal A.+B.=C.) | 3,776 |
| Fuel Weight (LT) | 7,099 |
| Cargo Load (LT) | 1,125 |

| | |
|---|---|
| Max.Full Load Displacement (LT) | 12,000 |

## F. APPROACH FOR TESTING

The first step to be taken is to determine whether the five-parameter method might be useful in the design process. From a mission standpoint, weaponry, radar, helicopter capabilities are logical capabilities, and from a design standpoint, speed, range, and displacement are the necessary characteristics for OPVs, as discussed in Chapter I. From a ship designer’s standpoint, weapons, radar, helicopters, and the extra personnel needed to service those systems translate into added weight. Added weight, of course, will increase displacement, which, in turn, can reduce speed and range capabilities. So, if the five-parameter method can be applied to demonstrate the effect that changes in speed, range, and displacement might have on a vessel, then the method may be useful. For example, if the SAR mission requires speed of “x” knots, and any added weight may reduce speed, the tests will immediately reveal whether the minimum speed requirement can be met if weight were added by increasing the ship’s length or beam or if propulsion capabilities should be increased.

Using Microsoft Excel, this author devised a calculable spreadsheet to compare the results when the five parameters associated with particular ships are analyzed. For military ships, data was modified by taking into account lower and upper limits when calculating resistance that a ship’s hull experiences move through water. As will be specifically discussed in the following section of this thesis, the lower and upper limits of resistance were included when calculating the lift to drag ratio and the appropriate Froude number. The end-result of the spreadsheet was that a rudimentary dashboard was created which indicates whether the length, beam, or payload must be reduced to achieve the desired speed, range, or displacement. Likewise, it permits the user to see the opposite effect by otherwise adjusting speed, range, and displacement.

As a parenthetical note, this author’s Excel calculations include a column which mirrors Dr. McKesson’s calculations, so that this author’s calculations and methodology could be considered credible. Once that credibility was established, then this author expanded the methodology by adjusting the data modifications for typical military vessels.

## G. METRIC CONVERSIONS—JANE'S DATA

Table 3 reflects the metric conversions that were needed to convert the data from Jane's in the Excel spreadsheet to a comparable format for the five-parameter approach, so as to accurately represent and analyze the data.

Table 3. Metric Conversions—Used to Convert Jane's Data

| Conversions for Selected Metrics | | |
|---|---|---|
| ft | meter | 0.3048 |
| LT | cubic ft salt water | 35 |
| LT | lbs | 2240 |
| HP | lbs*ft/minutes | 33000 |
| knots | m/seconds | 0.514444 |
| m/s | ft/minutes | ((m/s)*60)/(.3048) |

## H. DECOMPOSITION – LIFT TO DRAG RATIO AND FROUDE NUMBER – CARGO SHIP V. COMBAT SHIP

While the model built by Dr. McKesson utilizes cargo weight as a parameter, in this research, the ship being designed (OPV) is a combat ship, so mission package 'payload' weight is substituted for "cargo weight." The challenge faced was to identify, in general, the differences in calculating weight between a cargo and a military vessel, so as to be able to quantify the same in the five-parameter method. The most complex metric to analyze and understand was the L/D ratio and related Froude number. As indicated above, the lift to drag ratio and the volumetric Froude number are significant because they are used to calculate the estimate of the resistance that the ship hull may encounter. In turn, resistance is a factor for determining the power needed to propel the ship, which, in turn, can affect the ship's range and payload capacity. As such, a designer must predict resistance.

Lift to drag ratio represents the relationship of the ship's weight (i.e., lift) to the resistance that the ship's hull may experience (i.e., drag) (McKesson 2011, 736). Usually, resistance is not known, so it must be calculated. Generally, the simplified formula used is: L/D = OPC x (Power/Speed). OPC is the overall propulsive efficiency (McKesson, 2011, 736). The best attainable lift to drag ratio would be achieved if the OPC were 1.0 (McKesson, 2011, 736). In that case, the resistance would be at its lowest, since the efficiency of the hull would be at its highest. As mentioned previously, an OPC of 0.60 to 0.70 is generally acceptable. An OPC of 0.60 was used by McKesson in his illustrations, and is used in this thesis for hypothetical military ship.

The lift to drag formula for a cargo ship and a military ship often differs due to a variety of factors, most notable the shape of the hull. Cargo ships typically have a greater beam and length than do military ships. As such, the following formulas, albeit a bit more complicated, can be used to calculate resistance for such ships:

Cargo ship: $L/D = 5+40 \times Fn_{vol}^{-3.0}$

Combat ship: $L/D = 2.82+15.53 \times Fn_{vol}^{-3.4}$

Decomposing the formulas, the numbers 5 and 40 are typical lower and upper limits of resistance for a cargo ship, while 2.82 and 15.53 might be the respective counterparts for a military ship (McKesson, 2006 and 2011; F. Papoulias, personal communication, July 25, 2013; McKesson 2013). The higher numbers for cargo ships are plausible in view of their greater wetted surface, and the lower numbers for military ships make sense in view of their more streamlined hulls for speed.

The portion of the formula designated as $Fn_{vol}$ represent the volumetric Froude number. This too is a ratio, but it measures, in pertinent part, the resistance that a submerged item may find as it moves through a liquid (Gillmer and Johnson 1982). It is a useful number because it facilitates the comparison of different sized objects (Gillmer and Johnson 1982). The coefficients of -3.0 and -3.4 for cargo ships and military ships, respectively, are considered appropriate for said ships and are accepted as such in this thesis (McKesson 2006, 2011 and 2013; F. Papoulias, personal communication, July 25, 2013).

If the Froude number is to be used with the lift to drag ratio as a predictor of resistance, then the dependency of the lift to drag ratio on the Froude number should be tested to determine the strength or weakness of the relationship. Using the lift to drag ratio set forth above for cargo ships, McKesson plotted his data and concluded based upon the curve that it "... is not rigorously the absolute best performance ever observed, but is at least on the upper edge of the attainable performance space. It is also computationally simple, being Observed Best Attainable TF (Transport Factor) = 5+40 Fn-3" (McKesson 2011, 736). Dr. McKesson did not present his statistical analysis with respect to the noted relationship.

Using Dr. McKesson's approach as a guide, this author, performed similar tests to assess the dependency of the lift to drag ratio on the Froude number with respect to a military ship. Data from *Jane's* 33 military ships (see Table 4) was identified and plotted after several conversions of metrics were made for comparison purposes. A graph line was drawn to illustrate what relationship might exist and a trend line was inserted to determine predictability. The data, graph, and pertinent statistical analysis follow.

Table 4. Data from Jane's to Calculate L/D Ratio & Froude No. (Combat Ship)

| **Ship No.:** | **Froude No. (Jane's):** | **Lift/Drag Ratio (Jane's):** | **Lower Limit for Wave Resistance:** | **L/D Ratio Adj. for Lower Limit:** | **Froude No. Adj. for Lower Limit:** | **Arbitrary Increment to Illustrate Effect** | **Lift to Drag Ratio:** |
|---|---|---|---|---|---|---|---|
| | "X" | "Y" | a | Y-a | Y-calc | X_calc | Y_calc |
| | | | 2.8234 | | | 0.06 | |
| 1 | 0.897 | 39.631 | 2.8234 | 36.808 | 25.274 | 0.55 | 121.383 |
| 2 | 2.140 | 2.833 | 2.8234 | 0.010 | 3.992 | 0.61 | 86.201 |
| 3 | 1.151 | 34.139 | 2.8234 | 31.316 | 12.459 | 0.67 | 63.430 |
| 4 | 0.920 | 27.433 | 2.8234 | 24.610 | 23.411 | 0.73 | 48.100 |
| 5 | 1.236 | 15.220 | 2.8234 | 12.397 | 10.373 | 0.79 | 37.436 |
| 6 | 0.936 | 20.693 | 2.8234 | 17.869 | 22.291 | 0.85 | 29.810 |
| 7 | 1.265 | 32.120 | 2.8234 | 29.297 | 9.800 | 0.91 | 24.224 |
| 8 | 1.106 | 14.342 | 2.8234 | 11.519 | 13.859 | 0.97 | 20.048 |
| 9 | 0.898 | 27.340 | 2.8234 | 24.517 | 25.173 | 1.03 | 16.868 |
| 10 | 0.953 | 17.750 | 2.8234 | 14.927 | 21.136 | 1.09 | 14.409 |
| 11 | 1.106 | 12.049 | 2.8234 | 9.225 | 13.835 | 1.15 | 12.479 |
| 12 | 0.952 | 17.594 | 2.8234 | 14.770 | 21.160 | 1.21 | 10.946 |
| 13 | 0.939 | 19.121 | 2.8234 | 16.298 | 22.046 | 1.27 | 9.714 |
| 14 | 0.604 | 121.788 | 2.8234 | 118.965 | 88.905 | 1.33 | 8.713 |
| 15 | 0.940 | 20.127 | 2.8234 | 17.303 | 21.994 | 1.39 | 7.892 |
| 16 | 1.398 | 8.163 | 2.8234 | 5.339 | 7.793 | 1.45 | 7.214 |
| 17 | 0.966 | 16.631 | 2.8234 | 13.808 | 20.289 | 1.51 | 6.649 |
| 18 | 1.095 | 12.875 | 2.8234 | 10.052 | 14.216 | 1.57 | 6.174 |
| 19 | 1.344 | 28.676 | 2.8234 | 25.852 | 8.508 | 1.63 | 5.773 |
| 20 | 0.869 | 19.148 | 2.8234 | 16.324 | 27.883 | 1.69 | 5.432 |
| 21 | 0.975 | 21.278 | 2.8234 | 18.454 | 19.746 | 1.75 | 5.140 |
| 22 | 2.317 | 7.543 | 2.8234 | 4.720 | 3.715 | 1.81 | 4.889 |
| 23 | 1.732 | 9.833 | 2.8234 | 7.010 | 5.222 | 1.87 | 4.672 |
| 24 | 2.030 | 4.474 | 2.8234 | 1.651 | 4.222 | 1.93 | 4.484 |
| 25 | 0.863 | 46.829 | 2.8234 | 44.006 | 28.427 | 1.99 | 4.320 |
| 26 | 0.789 | 20.035 | 2.8234 | 17.212 | 37.588 | 2.05 | 4.176 |
| 27 | 0.768 | 24.817 | 2.8234 | 21.993 | 40.938 | 2.11 | 4.050 |
| 28 | 0.702 | 22.979 | 2.8234 | 20.156 | 54.624 | 2.17 | 3.938 |
| 29 | 2.194 | 3.286 | 2.8234 | 0.463 | 3.898 | 2.23 | 3.839 |
| 30 | 2.166 | 5.037 | 2.8234 | 2.213 | 3.945 | 2.29 | 3.752 |
| 31 | 0.939 | 12.990 | 2.8234 | 10.167 | 22.077 | 2.35 | 3.674 |
| 32 | 1.656 | 6.055 | 2.8234 | 3.232 | 5.617 | 2.41 | 3.604 |
| 33 | 0.552 | 117.373 | 2.8234 | 114.550 | 120.256 | 2.47 | 3.541 |

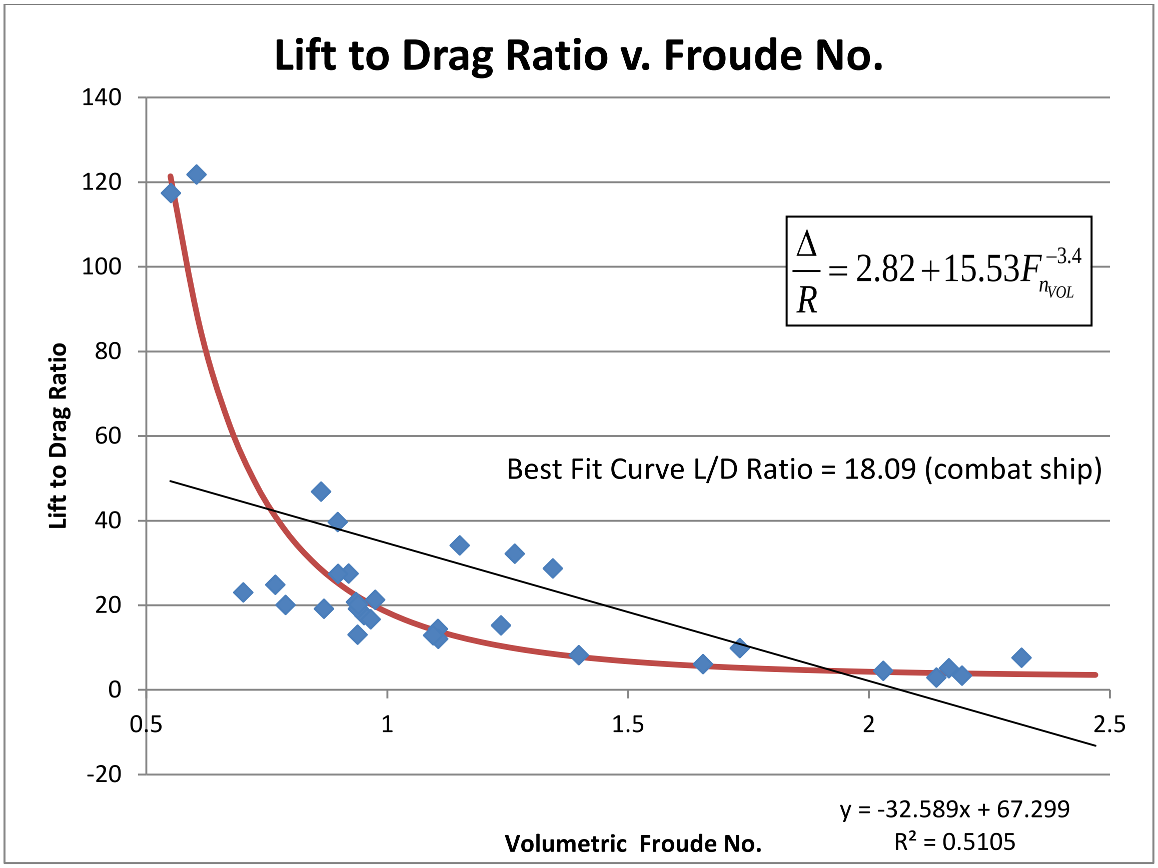



Figure 8. Effective Lift to Drag Ratio for Combat Ship

Table 5. Statistical Analysis of Figure 8

Statistical Analysis:

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.714512 |
| R Square | 0.510528 |
| Adjusted R Square | 0.494738 |
| Standard Error | 18.80922 |
| Observations | 33 |

With respect to the graph depicted in Figure 8, it can be seen that there is a cause and effect relationship between the independent variable (i.e., volumetric Froude number, as depicted on the "x" axis or the "cause") and the dependent variable (i.e., lift to drag ratio, as depicted on the “y” axis or the “effect”). The question arises whether the formula [$2.82+15.53 \times Fnvol^{-3.4}$] used to reflect the effect of changes in “y” due to changes in “x” can be a good predictor as replacement data is entered. If so, the formula may be useful; if not, then another formula should be identified or developed.

Different statistical methods may be used to determine if the formula is a good predictor. Before identifying which method to use, it must be determined whether the relationship is linear or nonlinear (e.g., curvilinear). In general, a linear relationship exists if data points seem to follow a single straight line, called a regression line, so as to suggest a relationship between the data on the “x” axis and the “y” axis. Generally speaking, a regression line is a straight line that is developed on a predetermined formula that reflects data on a graph (Oosterbaan 1994; Walpole and Myers 1972, 381 et seq.). Conversely, a nonlinear relationship exists if the data is so random, such that there is no such pattern. The straight line depicted in Figure 8 is a trend line, and it suggests that although there is a relationship between the volumetric Froude number and the L/D ratio so that the L/D ratio reacts as the volumetric Froude number is adjusted, maybe the relationship is not a lineal relationship, or, at a minimum, not a very strong lineal relationship. Several statistical methods may be used to test the fit and strength of the relationship, so as to determine how reliable the tool might be as a predictor in future testing. For purposes of this analysis, it may be sufficient to allow future researchers to consider the characterization of the relationship, as well as whether the five-parameter approach may be fortified as a tool predictability.

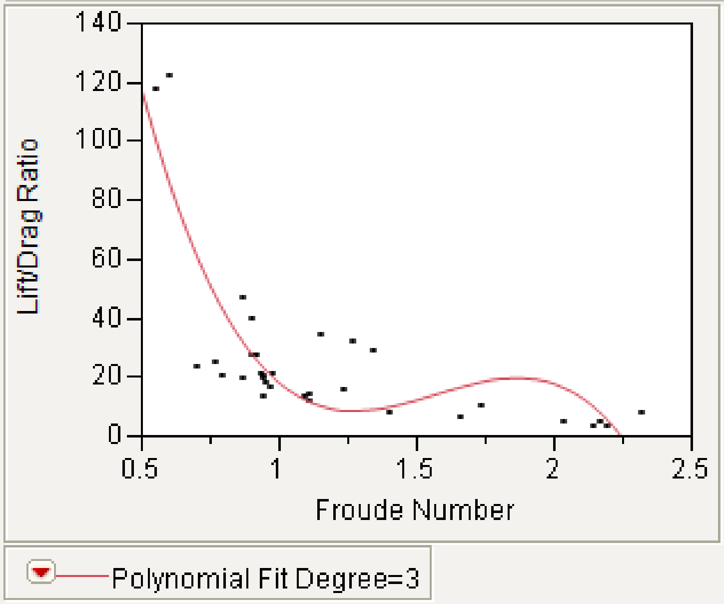
A common statistical method used to test how well data points fit in a regression model is the coefficient of determination method, sometimes referred to as the “Pearson correlation coefficient” (PCC). The R square factor, which can be computed based upon the PCC, generally indicates whether the formula used to analyze the relationship between data might be a useful forecaster. The resulting R Square factor will range from 0 to +1, where +1 would be considered as a "perfect positive" relation, and zero or 0 would indicate that there is no relationship. Most importantly, the usefulness of the R square factor as a predictor of changes in "y" due to changes in "x" will increase as it moves closer to +1 (Lohninger 1999; Longstreet 2009; Downing 1997).

Applying this knowledge to the statistical analysis generated by Excel and set forth in Table 5, it can be seen that based upon the 33 observations tested in Figure 8, Pearson’s R factor or “multiple R” as referred to by Excel, is 0.714512. That number squared is how the multiple R factor of 0.510528 was calculated. This number suggests that, yes, there is a positive relationship, so that changes in the volumetric Froude number will have a positive effect on the L/D ratio and can be subjected for further research by future researchers. However, it also indicates that the relationship based upon those 33 observations is not particularly strong, as 0.510528 sits about half way between 0 and +1. This result may be what Dr. McKesson experienced in his studies and what caused him to comment the relationship he found for cargo ships was “...not rigorously the absolute best performance ever observed, but is at least on the upper edge of the attainable performance space. It is also computationally simple...” (McKesson 2011, 736).

Analysis of bivariate data is another statistical method that may be helpful when deciding how well data points fit in a regression model, so as to determine the model's ability to predict changes in "y" (i.e., dependent variable) as "y" reacts to changes in "x" (i.e., independent variable). The term "bivariate" simply refers to data that has two variables (Wolfram Research 2013).

The graph depicted in Figure 9 reflects bivariate data approach and differs from the graph in Figure 8 in that it recomputes the L/D ratio and Froude numbers, thereby reducing the standard error from 18.80922 (See Table 5) to 15.69973, increasing the R Square value from 0.510528 (See Table 5) to 0.685154, and concluding that the bivariate data method may be the better method to better describe the fitness of the relationship between the sets of data. The bivariate data method is depicted in Figure 9, which follows:

## Bivariate Fit of Lift/Drag Ratio By Froude Number




### Polynomial Fit Degree=3

Lift/Drag Ratio = 30.236769 - 17.571796*Froude Number + 122.91956*(Froude Number-1.19388)^2 - 109.14655*(Froude Number-1.19388)^3

#### Summary of Fit

| | |
|---|---|
| RSquare | 0.685154 |
| RSquare Adj | 0.652584 |
| Root Mean Square Error | 15.69973 |
| Mean of Response | 24.55158 |
| Observations (or Sum Wgts) | 33 |

#### Lack Of Fit

#### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 3 | 15555.082 | 5185.03 | 21.0362 |
| Error | 29 | 7147.964 | 246.48 | Prob > F |
| C. Total | 32 | 22703.046 | | <.0001* |

Figure 9. Bivariate Fit of Life/Drag Ratio by Froude Number

## I. TESTING AND ANALYSIS OF RESULTS—EXCEL MODEL

The five-parameter method was applied to four ship designs and the results are reported and compared in Table 9:

Table 6. Comparison of Selected Designs Using Five-Parameter Method

Comparison of Selected Designs Using 5 Parameter Method

| | Ship #1 (McKesson) Cargo Ship: | Ship #2 (Hypothetical) Combat Ship: | Ship #3 Amazonas Class-OPV Combat Ship: | Ship #4 Modified Combat Ship: |
|---|---|---|---|---|
| Operational *Requirements*: | | | | |
| Full load displacement (LT) | 12,000 | 12,000 | 1,964 | 8,000 |
| Speed (knots) | 43 | 43 | 25 | 25 |
| Range (miles) | 5,000 | 5,000 | 5,500 | 5,500 |
| Cargo (LT) | 3,600 | 3,600 | 3,600 | 3,600 |
| Data (assumed or calculated): | Metrics | Metrics | Metrics | Metrics |
| Full Load Displacement (LT) | 12,000 | 12,000 | 1,964 | 8,000 |
| [Convert: Displacement-salt water(1lb.*35)(volume in cubic ft.) | 420,000 | 420,000 | 68,740 | 280,000 |
| [Convert: Volumetric Length (ft.) | 74.89 | 74.89 | 40.96 | 65.42 |
| [Convert: Volumetric Length (ft. to meters) (m) per second | 22.83 | 22.83 | 12.49 | 19.94 |
| Vk.(speed in (knots) | 43 | 43 | 25 | 25 |
| [Convert: knots-hr.-sec.] | 22.12 | 22.12 | 12.86 | 12.86 |
| [Convert: Feet per minute] | 4,354.17 | 4,354.17 | 2,531.50 | 2,531.50 |
| Fnvol ( Volumetric Froude no.) | 1.48 | 1.48 | 1.16 | 0.92 |
| L/D (cargo ship) [lower=5;upper=40];pwr=-1/3 | 17.39 | | | |
| L/D (military ship) [lower=2.82;upper=15.53]pwr=-3.4 | | 6.93 | 12.14 | 23.47 |
| Resistance (lbs) | 1,546,144 | 3,877,890 | 362,405 | 763,369 |
| EHP (hp) (“Effective Horsepower”) | 204,021 | 511,707 | 27,803 | 58,564 |

| | | | | |
|---|---|---|---|---|
| OPC | 0.6 | 0.6 | 0.6 | 0.6 |
| SHP (hp) ("Shaft Horsepower") | 340,036 | 852,844 | 46,338 | 97,607 |
| SFC (lbs/hp-hr) | 0.4 | 0.4 | 0.4 | 0.4 |
| Range (miles) | 5,000 | 5,000 | 5,500 | 5,500 |
| Fuel Weight (lbs) | 15,815,608 | 39,667,180 | 4,077,770 | 8,589,401 |
| Fuel Weight (LT) | 7,061 | 17,709 | 1,820 | 3,835 |
| Displacement minus Fuel (LT) | 4,939 | (5,709) | 144 | 4,165 |
| Wt of Power (lbs/hp) | 10 | 10 | 10 | 10 |
| Machinery Weight (LT) | 1,518 | 3,807 | 207 | 436 |
| Convert: Weight Avail for Cargo & Cargo Carriage (LT) | 3,421 | (9,516) | (63) | 3,730 |
| Carriage Multiplier (lbs/lb) | 2 | 2 | 2 | 2 |
| Cargo Carriage Weight (LT) | 2,281 | (6,344) | (42) | 2,486 |
| Cargo Load (LT) | 1,140 | (3,172) | (21) | 1,243 |
| <u>Summary</u>: | | | | |
| Cargo Ship: Machinery Weight (LT) (N/A-Combat) | 1,518 | | | |
| Cargo Ship: Cargo Carriage Weight (LT) (N/A-Combat) | 2,281 | | | |
| Cargo Ship: Light Ship Weight (LT) | 3,799 | | | |
| Fuel Weight (LT) | 7,061 | 17,709 | 1,820 | 3,835 |
| Cargo Ship: Cargo Load/Payload (LT) (N/A-Combat) | 1,140 | | | |
| Combat Ship: Weight of Items for Mission | Not Applicable | (5,709) | 144 | 4,165 |
| Full Load Displacement (LT) | 12,000 | 12,000 | 1,964 | 8,000 |
| Need Ship Length to Meet Req. (m) = | 126 | 126 | 69 | 110 |

| | | | | |
|---|---|---|---|---|
| Needed Beam to Meet Mission Req. (m) = | 26 | 26 | 18 | 24 |
| Conclusion: Does Design Meet Requirements? | NO | NO | NO | YES |

Table 7. Conversion Table for Selected Metrics

| Conversion Table for Selected Metrics | | |
|---|---|---|
| ft | meter | 0.3048 |
| LT | cubic ft salt water | 35 |
| LT | lbs | 2240 |
| HP | lbs x ft/min | 33000 |
| knots | m/s | 0.514444 |
| m/s | ft/min | ((m/s) x 60)/(.3048) |

Table 6 is divided into three sections: (1) Operational Requirements; 2. Data (assumed or calculated); and (3) Summary. Following is a brief discussion of how each of these sections were developed:

### 1. Operational Requirements

Operational requirements are those capabilities that are required for the ship to satisfy its intended use. They are minimum goals that must be met and, as such, are denoted in Table 6 as "given." For example, in Table 6, Ship 1, the cargo ship, must have a minimum full load displacement of 12,000 long tons, minimum speed of 43 knots, minimum range of 5,000 miles, and a minimum cargo carrying capability of 3,600 long tons. A brief definition for each follows:

- Full Load Displacement: Full load displacement is the weight of the water that a ship replaces; more directly, Archimedes' principle tells us that it is the weight of the ship, itself, plus its cargo when fully loaded (Barrass 2004). 1 long ton equals 2,240 pounds (Gillmer and Johnson 1982).
- Speed (knots) Ship speed in knots: 1 mile per hour = 0.8690 knots per hour (Gillmer and Johnson 1982).
- Range (miles) This is the maximum distance that a ship can travel before running out of fuel (MacKenzie 2012).
- Cargo (LT) This is the weight of the payload or other items being carried (Gillmer and Johnson 1982).

### 2. Data (Assumed or Calculated)

Data used for illustrating the five-parameter model was either assumed or calculated. The assumed data was generally based upon accepted ship characteristics or historical data, such as the OPC of 0.60, described previously. Calculable data, such as the calculation of full load displacement, is illustrated in whether the data was assumed or calculated and how calculations were performed, table below was devised. It isolates the data above for Ship #1 [Dr. McKesson's cargo ship] but adds the column "How Derived." The "How Derived" column was taken from the Excel worksheet which supports Table 6, and the mathematics therein were developed by Dr. McKesson and reviewed by Dr. Papoulias. The mathematics for Ships #2 through #4 are the same, except that the different formula for computing the L/D ratio and volumetric Froude number for combat vessels, as discussed above, is used.

## Table 8. Assumed or Calculated Data: Mathematics Illustrated

Comparison of Selected Designs Using 5 Parameter Method

| Operational *Requirements*: | Ship #1 (McKesson) Cargo Ship: |
|---|---|
| Full load displacement (LT) | 12,000 |
| Speed (knots) | 43 |
| Range (miles) | 5,000 |
| Cargo (LT) | 3,600 |

| Data (assumed or calculated): | Metrics | How Derived |
|---|---|---|
| Full Load Displacement (LT) | 12,000 | Given |
| [Convert: Displacement-salt water(1lb.*35)(volume in cubic ft.) | 420,000 | 12,000 x 35 |
| [Convert: Volumetric Length (ft.) | 74.89 | 420000^⅓ |
| [Convert: Volumetric Length (ft. to meters) (m) per second | 22.83 | 74.89 x 0.3048 |
| Vk.(speed in (knots) | 43 | Given |
| [Convert: knots-hr.-sec.] | 22.12 | 43 x.5144 |
| [Convert: Feet per minute] | 4,354.17 | 22.12 x 60/.3048 |
| Fnvol ( Volumetric Froude no.) | 1.48 | 22.12/(SQRT(9.81 x 22.83) |
| L/D (cargo ship) [lower=5;upper=40];pwr=-1/3 | 17.39 | 5+40 x C30^(-3) |
| L/D (military ship) [lower=2.82;upper=15.53]pwr=-3.4 | | |
| Resistance (lbs) | 1,546,144 | (12000/17.39) x 2240 |
| EHP (hp) ("Effective Horsepower") | 204,021 | (1546144 x (43x0.51444)x60)/0.3048/33000 |
| OPC | 0.6 | Assumed |
| SHP (hp) ("Shaft Horsepower") | 340,036 | 204021/0.6 |
| SFC (lbs/hp-hr) | 0.4 | Assumed |
| Range (miles) | 5,000 | Given |
| Fuel Weight (lbs) | 15,815,608 | (340036 x 0.4 x 5000)/43 |
| Fuel Weight (LT) | 7,061 | 15815608/2240 |
| Displacement minus Fuel (LT) | 4,939 | 12000-7061 |
| Wt of Power (lbs/hp) | 10 | Assumed |
| Machinery Weight (LT) | 1,518 | (10 x 340036)/2240 |
| Convert: Weight Avail for Cargo & Cargo Carriage (LT) | 3,421 | 4939-1518 |
| Carriage Multiplier (lbs/lb) | 2 | Assumed |

| | | |
|---|---|---|
| Cargo Carriage Weight (LT) | 2,281 | 2 x 1140 |
| Cargo Load (LT) | 1,140 | 3421-2281 |
| Summary: | | |
| Cargo Ship: Machinery Weight (LT) (N/A-Combat) | 1,518 | |
| Cargo Ship: Cargo Carriage Weight (LT) (N/A-Combat) | 2,281 | |
| Cargo Ship: Light Ship Weight (LT) | 3,799 | |
| Fuel Weight (LT) | 7,061 | |
| Cargo Ship: Cargo Load/Payload (LT) (N/A-Combat) | 1,140 | |
| Combat Ship: Weight of Items for Mission | Not Applicable | |
| Full Load Displacement (LT) | 12,000 | |
| Need Ship Length to Meet Mission Req. (m) | 126 | 22.83 x 5.5 (see discussion below) |
| Needed Beam to Meet Mission Req. (m) | 26 | B = Length$^{2/3}$ + 1 (see discussion below) |

#### a. Summary

The summary portion of Table 6 is incorporated into the comments of testing results for each of the four ships. Those comments follow.

#### b. Ship Design #1

This ship design is simply a reiteration of Dr. McKesson's hypothetical cargo ship. It was included to demonstrate that the formulas used to calculate the resulting ship characteristics are consistent with those of Dr. McKesson. This author arrived at the same conclusion as Dr. McKesson, both mathematically and from a decision-making standpoint, and, as such, it may be concluded that this author's formulas are reasonably accurate and supportive.

As mentioned above, HSSL's operational requirement called for the ship to be capable of a payload of 3,600 LT, speed of 43 knots, range of 5,000 nautical miles, and a ship whose displacement would not exceed 12,000 tons and whose length would not exceed 560 feet in length. The conclusion arrived at by Dr. McKesson and as illustrated in Table 6, the design is infeasible, since only 1,140 LT of cargo can be carried, far short of the 3,600 LT required.

#### c. Ship Design #2

This ship design converts the formulas from a cargo ship design to what is generally accepted as a military ship design. As described above, this simply means that the lift to drag ratio and coefficient used to calculate the Froude number have been modified to account for the more streamlined hull configuration used for military ships than for cargo ships.

Also, the line-item description for what might be carried on a cargo ship (e.g., machinery weight, cargo carriage weight, and cargo weight) has renamed and set forth on a separate line in the spreadsheet for what might be carried on a military ship (e.g., weaponry, helicopters, and other mission-specific items). This was done simply to more accurately depict the nature of the items related to the cargo carrying requirement of 3,600 LT for the military ship.

The result is that the design of this hypothetical military ship is infeasible. The ship would need 17,709 LT of fuel, which surpasses the full displacement of 12,000 LT. As such the design must be rejected.

#### d. Ship Design #3

This ship design mirrors that of the Amazonian class OPV which is currently being used by Brazilian Navy. Notably, the operational requirements were adjusted from the hypothetical ship requirements of 12,000 LT displacement, speed of 43 knots, and range of 5,000 nautical miles, to the actual capabilities of that OPV of 1,964 LT displacement, speed of 25 knots, and range of 5,500 nautical miles, to determine if it could carry the required payload of 3,600 LT. The result was that it could carry only 144 LT. Interestingly, however, the resulting length and beam of 89.03m and 12.85m, respectively, of the OPV, as recalculated by the spreadsheet, was nearly identical to the published dimensions for that OPV design. That fact seems to further suggest that the testing using the five-parameter method might be a reasonable tool for its stated purpose.

#### e. Ship Design #4

This ship takes its shape from Ship 3 (i.e., Amazonian class OPV) and changes only the displacement; it is increased from 1,964 LT to the arbitrary value of 8,000 LT. The result was that the ship could carry a payload of 4,514 LT, far more that the requirement of 3,600 LT. However, to handle the displacement, the ship’s length and beam must be extended to 146.52m and 18.45m, respectively. Of course, a concern will be what the cost of such a ship might be, as cost will be a factor of determining feasibility from an overall standpoint. That topic has been studied by other NPS students and may be ripe for re-examination if the noted design is to be pursued.

Figure 10. Figure 10. Brazilian Amazonas Class OPV (Net International 2012)

As a separate but related metric reported in the summary as Table(s) 6 and 8, the approximate length and beam that would be needed in order for the ship to satisfy the design requirements is reported. This computation was not included by Dr. McKesson in his articles; rather, it was added by this author as supplemental information. What makes the calculation interesting in conjunction with the use of the five-parameter tool, is that length and beam are lineal measurements and the five-parameter tool uses volumetric measurements; mathematically, volumetric measurements cannot be converted to lineal measurements. Yet, there is a relationship between the volume of a ship and the length and the beam. Logically, the more cargo or payload that is to be carried, the greater the ship length and the beam that would be required. This thesis suggest that this relationship can be quantified, at least as an approximation, so that the early stage ship designer who uses the five-parameter tool can have some idea of the length and beam of the resulting ship design.

In order to quantify the relationship between volume and length and beam, the concept of Dr. McKesson's Best Practices Curve was used. Dr. McKesson used that approach to analyze the relationship between the Froude number and the L/D Ratio to arrive at his modified L/D ratio for cargo ships of 17.39. Essentially, he plotted the Volumetric Froude numbers in his data base against the life to drag ratio of the ships in that same data base. Similarly, this author plotted the displacement data of the 33 ships from Jane's that were included in this thesis, as recalculated for use by the five-parameter tool, and plotted that data against the lengths that were reported in Jane's for those same ships. Regression analysis was performed to evaluate the strength of the relationship between the length of the ships and their displacement. The resulting factor of R2 of 86.14 indicated that the relationship was strong, thereby suggesting that displacement may be a good predictor of the length that would be needed for whatever displacement might be required by the stakeholder. Then, factor of 5.5 was derived by averaging the ratios of the 33 ships, indicating that, on average, the volumetric length was 5.5 times greater than the length. Then, by dividing the ship's volume by the factor of 5.5, the approximate length of the ships needed to carry that volume was calculated. The beam was calculated simply a using the formula of Beam = Length to the 2/3rds power, plus 1, which can be expressed as B = L2/3+1)  (Barrass 2004). By way of illustration, this approach was used to calculate the approximate ship length of 126m and beam of 26m that is reported in Table 8. The supporting graph and calculations follow:

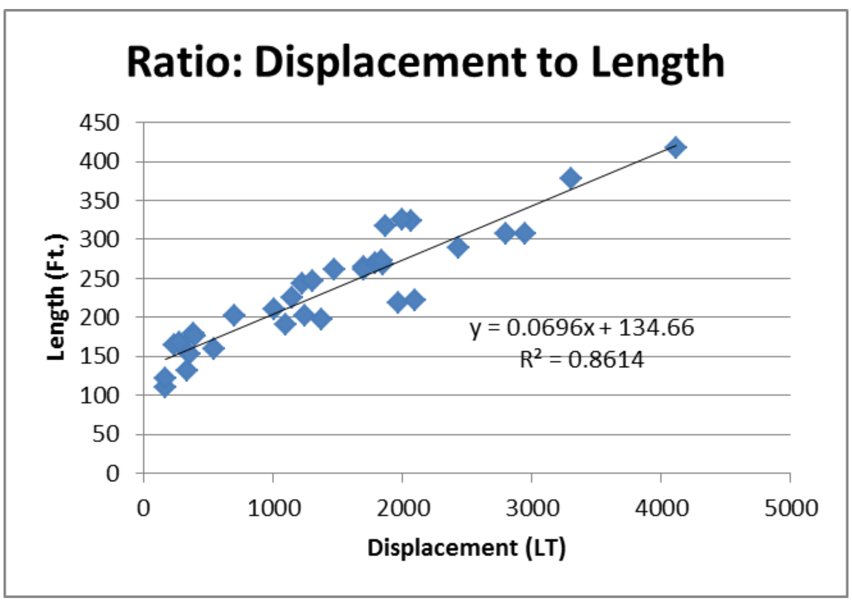



Figure 11. Ratio: Ship's Displacement to Length

Table 9. Ratio: Displacement to Length of Ship

| Ship No.: | Displacement (lbs) | Displacement (LT) | Length (ft.) | Ratio of Displ. To Length |
|---|---|---|---|---|
| 1 | 5442200 | 2430 | 290 | 8.4 |
| 2 | 848800 | 379 | 179 | 2.1 |
| 3 | 9211000 | 4112 | 418 | 9.8 |
| 4 | 4012400 | 1791 | 270 | 6.6 |
| 5 | 7392000 | 3300 | 378 | 8.7 |
| 6 | 2248800 | 1004 | 210 | 4.8 |
| 7 | 4188800 | 1870 | 317 | 5.9 |
| 8 | 4640800 | 2072 | 323 | 6.4 |
| 9 | 6261200 | 2795 | 308 | 9.1 |
| 10 | 3798600 | 1696 | 264 | 6.4 |
| 11 | 2742600 | 1224 | 243 | 5.0 |
| 12 | 3807400 | 1700 | 262 | 6.5 |
| 13 | 4138000 | 1847 | 268 | 6.9 |
| 14 | 4398200 | 1963 | 218 | 9.0 |
| 15 | 4118200 | 1838 | 273 | 6.7 |
| 16 | 879600 | 393 | 175 | 2.2 |
| 17 | 2568400 | 1147 | 225 | 5.1 |
| 18 | 2912400 | 1300 | 246 | 5.3 |
| 19 | 4479800 | 2000 | 325 | 6.2 |
| 20 | 6607200 | 2950 | 307 | 9.6 |
| 21 | 3304800 | 1475 | 262 | 5.6 |
| 22 | 527000 | 235 | 164 | 1.4 |
| 23 | 791400 | 353 | 153 | 2.3 |
| 24 | 377000 | 168 | 110 | 1.5 |
| 25 | 1221400 | 545 | 159 | 3.4 |
| 26 | 3086400 | 1378 | 197 | 7.0 |
| 27 | 2464800 | 1100 | 190 | 5.8 |
| 28 | 2799800 | 1250 | 202 | 6.2 |
| 29 | 615000 | 275 | 168 | 1.6 |
| 30 | 381400 | 170 | 121 | 1.4 |
| 31 | 738600 | 330 | 131 | 2.5 |
| 32 | 1567400 | 700 | 201 | 3.5 |
| 33 | 4706800 | 2101 | 222 | 9.4 |
| | Average Ratio: Displacement to Length | | | **5.5** |

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# IV. CONCLUSION AND RECOMMENDATIONS

The questions addressed by this thesis are whether the NPS approach to MBSE design concept can be used to allow a ship synthesis model to link ship design factors with ship operational considerations and whether such methodology can be expanded beyond the ship design process. This thesis answers these questions in the affirmative, and considers them in the context of determining the usefulness of the approach while determining its application of designing OPVs for engaging in SAR, MIO, and ASuW missions.

With respect to the design of OPVs, as well as other types of ships, a continuing challenge within the ship building industry has been to enable designers to synthesize and model “what if” scenarios as modifications to designs are proposed. If such modifications and their effects can be illustrated early in the design process, costly redesigns and the modifications might be avoided or minimized, both in the ship building stage and later in the ship’s life cycle.

Ship designers have long used a variety of traditional design methods and tools for synthesizing and modeling. The choice of methods may be based upon past practices, familiarity with the tools, and what may be affordable. As suggested when discussing the various traditional and non-traditional tools, improvements in tooling are being made on an ongoing basis, and designers should consider adding such tools to their tool kits as the complexity of ship designs and synthesizing and modeling increases.

A shortcoming in the ship design process is that each proposed design, whether traditional or not, must undergo the same, rigorous, time consuming and likely expensive process. Dr. McKesson’s five-parameter method may alleviate this problem, or, at least open the door to create efficient tools to facilitate testing in the early stages of ship design. The goal would be to further develop such methodology and tooling to streamline the process, thereby reducing time and associated costs.

It is recommended that further research be conducted with respect to using the five-parameter methodology, as it is not without its shortcomings. As can be seen from the discussion of the statistical analysis concerning the L/D ratio, the Froude number can explain and predict only about 51 percent to 68 percent (R square factor ranging of .51 to .68) of the resulting L/D ratio. The suggestion here is that that the formula, itself, as well as the data from Jane’s or other sources, should be further scrutinized for relevance. As such, this should either increase the confidence level in the L/D ratio as one of the five parameters or seek other metrics that would increase the confidence level in the use of the tool.

Additionally, it is recommended that the other parameters included as “assumed,” or based upon generally accepted formulas and concepts, such as the OPC of 0.60 and the cargo carrier to cargo ratio of 2:1, be re-examined to better assure their relevance.

One approach to increase the level of confidence in the five-parameter method might be to ask those persons who perform subsequent testing with sophisticated tooling to report whether the Dr. McKesson's tool mistakenly allowed designs to move to the next level of testing, when they should have been rejected in the initial testing. Further, possibly the five-parameter tool could be used in or as a supplement to the NPS dashboard, so as to further measure the reliability of the McKesson methodology. As a final recommendation for further research, the relationship between the output generated by the five-parameter tool, such as displacement and length and beam, should be revisited, as those metrics should be useful to the early-stage designer.

There is no reason why the NPS approach to MBSE design cannot be used beyond ship design. In general, the methodology calls for the identification of the problem, an examination of data, a determination of relationships among the various sets of data, the establishment of what results may be acceptable through statistical or other methods, and the formulation of measures of effectiveness against which to measure results.

Lastly, the words of Dr. McKesson come to mind. He reminds us to keep a proper perspective when searching for a methodology and tool to assist us in our quest. Repeating his comment and philosophy when discussing his five-parameter method, he said that it “... is not rigorously the absolute best performance ever observed, but is at least on the upper edge of the attainable performance space. It is also computationally simple...” (McKesson 2011, 736). Sometimes, “simple” is better, and often, repetition is the branding iron of knowledge.

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